

## APPENDIX F-1

## ELECTRIC GENERATION PLANTS

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Two large utilities -- Southern California Edison Company (Edison), a privately owned utility, and the Los Angeles Department of Water and Power (DWP), a municipal utility -- supply nearly all of the Los Angeles basin and vicinity with its electrical energy. Prior to 1950, even if sulfur oxides air pollution had been perceived as a problem, the utilities would not have been involved; almost all of their energy was generated by pollution-free hydroelectric plants. However, during the 50s and 60s, as prime hydro sites became rarer, more and more steam plants designed to burn gas or oil were constructed. Of course, it was cheapest to build them beside the customers they were to supply, and thus within the air basin. By 1967, 86.8 percent and 83.7 percent, respectively, of Edison's and DWP's capacity consisted of these oil and gas-fired plants. After 1967 the advent of nuclear steam plant technology and construction of out-of-basin coal-fired steam plants began to reduce the utilities' dependence on in-basin oil and gas-fired steam plants in percentage terms. However, in absolute magnitudes, this dependence continued to grow, spurred by the basin's increasing demand for energy. In 1976 Edison possessed eleven oil and gas-fired steam power plants totalling 8786 megawatts (MW), all but 130 MW of it in the air basin. For its part, DWP owned four oil and gas-fired steam plants totalling 3199 MW of power. This amounted

to 65 percent and 54 percent, respectively, of Edison's and DWP's total capacity in 1976 (Los Angeles Department of Water and Power, 1976; Southern California Edison Co., 1976).

In 1967 the sulfur oxides pollution problem from electric utilities was still primarily a potential one. The bulk of energy produced in the in-basin plants originated from combustion of natural gas which essentially results in no sulfur oxides emissions. This policy was followed because of the pollution-minimizing character of natural gas, its artificially low regulated price relative to oil, and the fact that when gas is burned in plants less maintenance is required. However, as available natural gas supplies dwindled, both utilities were forced to substitute sulfur-bearing fuel oil to an ever greater extent. This switch to oil combined with construction of new oil-fired steam capacity resulted in hundreds of tons per day of increased sulfur oxides emissions from electric utilities over the decade from 1967 to 1977.

As early as 1958, regulatory authorities had recognized this problem by requiring utilities to burn low sulfur (less than 0.5 percent by weight) fuel oil, dependent upon natural gas supply conditions. By 1968 the rule had been changed to hold regardless of natural gas supply conditions. But in Edison's case, for example, electricity generation from oil rose 455 percent between 1968 and 1976. Total allowable sulfur oxides emissions also rose by the same proportion. This growth in sulfur oxides emissions was further restrained during 1977 when local regulations were amended to prohibit burning of fuel oil containing over 0.25 percent sulfur by weight.

Provision of large quantities of low sulfur fuel oil is costly compared to purchase of high sulfur oil. Thus the question arises, "Have rules concerning the sulfur content of fuel been set at an economically efficient level?" That question can be investigated by comparison to the emissions control costs facing other industries that might participate in a market for transferable licenses to emit air pollutants. However, as a prelude to that study, the costs and other relevant characteristics of various emission control strategies for electric utilities need to be determined. Furthermore, there is some question as to whether the current strategy of burning low sulfur fuel is the best way to achieve existing air quality levels. This chapter attempts to fill these needs by identifying the costs and other relevant factors associated with two different methods of achieving sulfur oxides emission levels from power plants equivalent to those if rules permitting the maximum sulfur content of fuel to be 5 percent, 2.5 percent, 1 percent, 0.5 percent, 0.25 percent, 0.1 percent, and .025 percent were in effect. The two methods of emission control are burning fuel oil of the desired sulfur content or installing scrubbers on plant smokestacks to remove sulfur oxides from exhaust gases while burning higher sulfur fuel.\*

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\*Purchase of natural gas is also a viable  $SO_x$  control technique. However, the availability of natural gas depends on federal natural gas allocation policies which are beyond the control of the electric utility industry. In this paper, the emissions and costs facing the electric utility industry will be calculated for a special case, that is for 100 percent fuel oil combustion. If natural gas supplies become available at a price competitive with oil, then emissions and hence potential demand for licenses to emit sulfur oxides air pollutants are easily scaled downward.

Given a choice between burning low sulfur oil and installing scrubbers, it is shown here that burning low sulfur fuel oil is in fact the cost-effective method of emission control (given 1977 prices for fuels and emissions control equipment). The marginal cost per ton of sulfur oxides from burning progressively lower sulfur fuels is calculated. This allows calculation of the utilities' maximum demand for licenses to emit sulfur oxides air pollutants if they were placed in a situation where utilities have to pay some fee per ton of  $SO_x$  emitted.

#### FUEL COSTS

Fuel costs affect both the choice of strategy for emissions control and the extent to which any strategy is pursued. Ceteris paribus, as the price difference between high and low sulfur fuel rises, the option of burning low sulfur fuel becomes less attractive relative to the other two options of burning high sulfur fuel oil and scrubbing emissions or simply burning high sulfur fuel oil and not scrubbing. In the simplest case, suppose there are only two grades of oil -- high and low sulfur. Suppose the utility must pay \$ $\ell$  for every unit of sulfur oxides emitted by it. High sulfur oil releases  $\alpha_h$  units of sulfur oxides per unit of oil; low sulfur oil releases  $\alpha_\ell$  units. Let the price of low and high sulfur oil be, respectively,  $P_h$  and  $P_\ell$ . Suppose that scrubbing emissions costs \$ $e$  per unit of oil burned and that after scrubbing, low and high sulfur oil release, respectively,  $\beta_\ell$  and  $\beta_h$  units of sulfur oxides per unit of oil burned.

The total costs of purchasing and burning one unit of oil then depends on whether emissions are scrubbed and the purchase price.

TABLE 1  
TOTAL COST OF BURNING ONE UNIT OF OIL

	Low Sulfur Oil	High Sulfur Oil
Emissions are Scrubbed	$e + l\beta_l + P_l$	$e + l\beta_h + P_h$
Emissions are not	$l\alpha_l + P_l$	$l\alpha_h + P_h$

The utility will select the strategy associated with the smallest total cost in Table 1. Clearly as  $(P_l - P_h)$  rises, the option of burning high sulfur fuel oil becomes more attractive.

Estimated prices for fuel oil as a function of sulfur content that will be used in this study are given in Table 2 and Figure 1 (Cass and Rogerson, 1980). Note that 1977 prices are used. These older prices are used because current prices are extremely variable due to continuing price rises and shortages, and it is difficult to determine what current market prices are (Riess, 1979; Hyska, 1979; Felger, 1979). Therefore, 1977 prices (which were fairly stable for two to three years) may give a better picture of long-term relative prices, that is, the premium commanded by lower sulfur fuel in a stable oil market.

TABLE 2  
ESTIMATED 1977 PRICE OF RESIDUAL FUEL OIL  
BY SULFUR CONTENT

<u>% Sulfur</u>	<u>Price</u>
0.025	\$16.90 (extrapolated)
0.10	15.80
0.25	14.50
0.50	13.75
1.0	13.00
2.5	11.00
2.5+	10.00

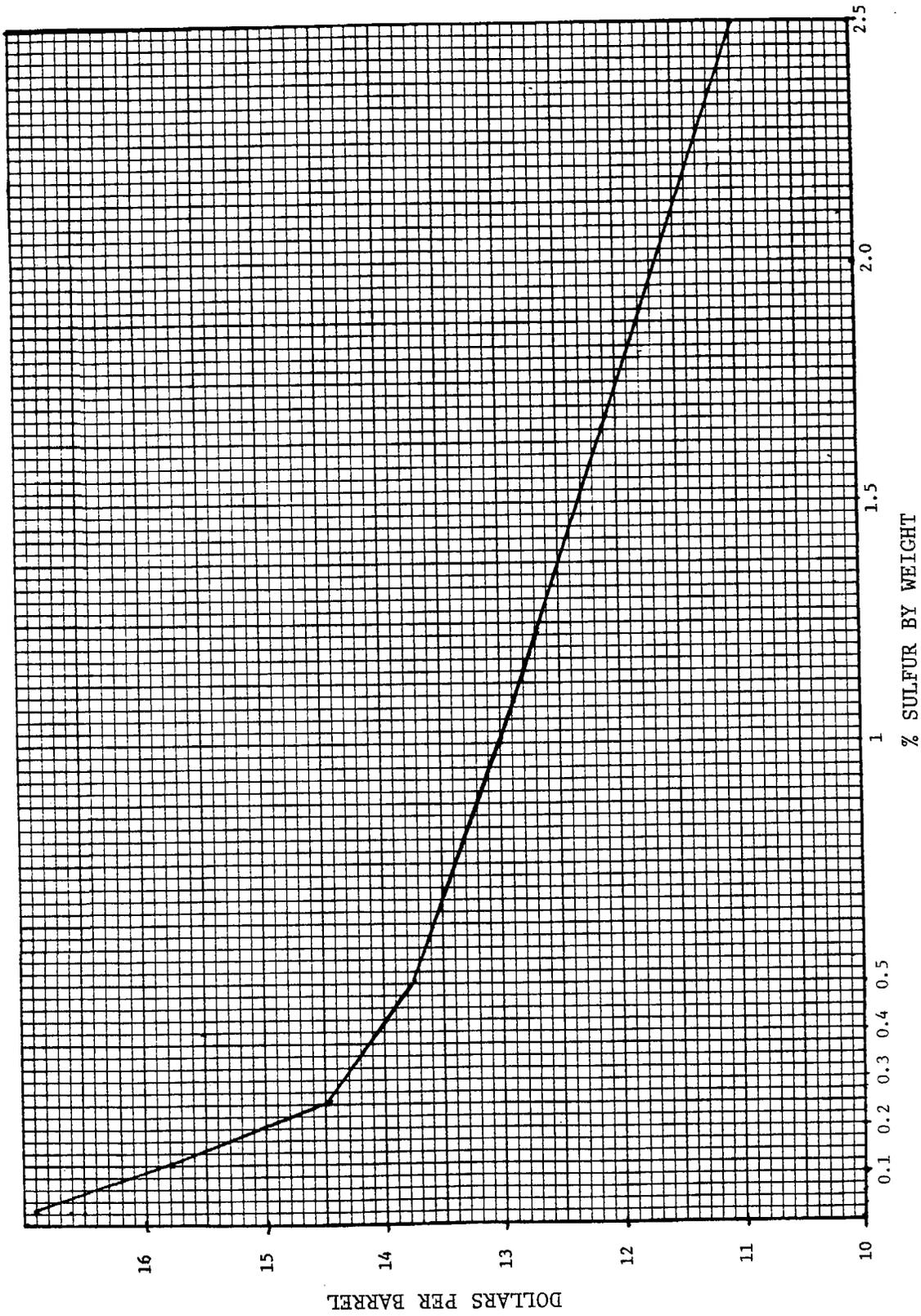


Fig. 1 Prices of Fuel Oil in 1977  
As a Function of % Sulfur by Weight

## CAPACITY FACTORS

Capacity factors reflect the percentage of a generating station's potential electricity production that is actually used during a given year. Since the capital cost of scrubber installation is the same whether or not the plant is used continuously at full load, capacity factors may affect the cost of emission control per barrel of fuel oil burned.

Capacity factors used in this study are those predicted for 1980 by Edison and DWP. Work was begun on this study using the utilities' 1977 predictions for 1980. Current (1979) predictions for 1980 subsequently were obtained and they differ insignificantly from the earlier version. Hence calculations based on the 1977 forecast for 1980 have been used herein.

Tables A-1 and A-2 at the end of this chapter give the projected capacity factors of the various plants. Table A-3 presents the heat rates. Based on these tables, Tables A-4 and A-5 give the projected oil use of the plants under conditions of low natural gas supply.

## SCRUBBER COSTS

Estimates of the cost of installing and operating flue gas scrubbing units can be obtained from two sources: an SRI International study (SRI International, 1978) done for Edison, and an Aerospace Corporation study (Leo and Rossoff, 1978) done for the California Air Resources Board. The former uses 1978 dollars and the latter uses 1977 dollars. Both estimate costs for a system designed to remove

90 to 95 percent of the  $\text{SO}_2$  formed during the combustion of a fuel oil containing .5 percent sulfur. Therefore the cost estimates should be comparable.

Tables A-6 and A-7 give the estimated capital cost of scrubber installation in dollars per KW. Tables A-8 and A-9 present operating costs. Neither study presented estimates for every plant. In the cases where no scrubber cost estimates were given for a particular generating unit, a cost estimate is taken equal to the average overall generating units for which specific information is available. For each plant the average of the SRI and Aerospace figures is calculated, and this is the cost figure that is used in this study.

Tables A-10 and A-11 present the annualized scrubbing costs for the various units. An annual charge of 20 percent of the total capital investment is levied to account for interest payments, taxes, and insurance. The Aerospace study used 19 percent; the SRI study used 21 percent. Edison apparently uses 20 percent for its own planning purposes (McCrackin, 1977).

#### LEAST COST EMISSIONS CONTROL STRATEGIES

The scrubber cost estimates were for systems designed to remove 90 to 95 percent of the  $\text{SO}_2$  which results when burning 0.5 percent sulfur fuel oil.<sup>1</sup> The costs of scrubbing emissions from other grades of fuel would be comparable (Leo, 1979), so it will be assumed that scrubbers could be used in conjunction with the combustion of any grade of fuel oil and that 90 percent of the  $\text{SO}_2$  could be

removed. The only exception is that for use with 0.5 percent sulfur fuel it will be assumed that 95 percent of the  $\text{SO}_2$  is removed to give the scrubbers full benefit of any doubt.

Table 3 shows the price differences which exist between various grades of residual oil.

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TABLE 3  
PRICE DIFFERENCE BETWEEN FUEL OIL GRADES  
AS A FUNCTION OF SULFUR CONTENT

<u>Grades of Oil</u>	<u>Price Difference</u>
2.5 <sup>+</sup> % vs. .5%	\$3.75
2.5 % vs. .25%	2.50
1 % vs. .1%	2.80
.5 % vs. .025%	3.15

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In Tables A-10 and A-11 at the end of this discussion, it is shown that the minimum cost of scrubbing emissions at any electric generating unit is \$3.59 per barrel of fuel oil consumed. Therefore by reference to Table 3 we see that the only situation in which it might be marginally profitable to install scrubbers instead of to burn low sulfur oil in any unit is to burn very high sulfur oil while scrubbing to 0.5 percent sulfur oil. Aside from Haynes Unit 6 and

Alamitos units 5 and 6 it is never even marginally profitable to install scrubbers. In the next section it is therefore assumed that the least cost control technology is to burn low sulfur oil.

#### DERIVED DEMAND FOR LICENSES TO EMIT SULFUR OXIDES AIR POLLUTANTS

Suppose that a license entitles the holder to emit one ton of  $SO_2$  into the atmosphere. (Variations such as perpetual licenses can be easily handled. The algebraically simplest case is treated here.) There are  $6.384(x)$  pounds of sulfur oxides emitted from burning a barrel of  $(x)$  percent sulfur oil. Let  $\ell$  be the price of a license. Let  $p_x$  be the price per barrel of  $x$  percent sulfur oil. Then the total cost,  $c$ , to the utility of burning one barrel of  $x$  percent sulfur oil is

$$c = \ell \left( \frac{\$}{\text{ton}} \right) \cdot 6.384[x] \left( \frac{\text{lbs. } SO_x}{\text{barrel}} \right) \cdot \left( \frac{1 \text{ ton}}{2000 \text{ lbs.}} \right) + P_x \left( \frac{\$}{\text{barrel}} \right)$$

This is the "full" price of a barrel of  $x$  percent sulfur oil when the cost of emissions control is considered to be part of the price.

The utility obviously chooses to burn the grade of fuel such that the full price is minimized. Table 4 presents the full price for the grades of oil presented in this paper.

TABLE 4  
 FULL PRICE PER BARREL OF OIL AS A  
 FUNCTION OF SULFUR CONTENT

<u>% Sulfur by Weight</u>	$\ell \frac{6.384}{2000} x + p_x$ (Dollars per Barrel)
0.025	$-3$ $0.08 \times 10^3 \ell + 16.90$
0.10	$-3$ $0.32 \times 10^3 \ell + 15.80$
0.25	$-3$ $0.80 \times 10^3 \ell + 14.50$
0.50	$-3$ $1.60 \times 10^3 \ell + 13.75$
1.0	$-3$ $3.19 \times 10^3 \ell + 13.00$
2.5	$-3$ $7.89 \times 10^3 \ell + 11.00$
4.0	$-3$ $12.77 \times 10^3 \ell + 10.00$

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Because price is a convex function of sulfur content,  $x$ , it is true that the utility's choice of  $x$  is a decreasing function of  $\ell$ . When the price of a license,  $\ell$ , is zero, the highest sulfur oil is chosen to minimize costs. As  $\ell$  rises the utility eventually chooses  $x = 2.5$  percent,  $x = 1$  percent, etc., until at some point it chooses  $x = .025$  percent. Table 5 presents the fuel oil sulfur content specifications which minimize the total cost of oil as a function of the price of a license to emit sulfur oxides air pollutants.

TABLE 5  
 CHOICE OF SULFUR CONTENT WHICH MINIMIZES  
 THE FULL PRICE OF OIL AS A FUNCTION  
 OF THE PRICE OF A LICENSE TO EMIT SULFUR OXIDES

Price of a license to emit a ton of SO <sub>x</sub> , in 1977 dollars	Sulfur content of fuel chosen (x), in % by weight
\$ 0 to \$ 210	4.0
210 to 420	2.5
420 to 470	1.0
470 to 940	.5
940 to 2720	.25
2720 to 4590	.10
4590 and up	.025

Three points should be noted. First, a smoothed control cost function can of course be obtained by blending oils of differing sulfur content. Second, the choice of whether to include the endpoints of the intervals in the left-hand column of Table 5 is arbitrary. Third, the last open-ended interval is based on the assumption that 0.025 percent sulfur oil is the lowest sulfur oil likely to be obtained under any circumstances.

If the utilities' choice of fuel sulfur content followed Table 5, we can calculate the demand for licenses and amount of sulfur released into the atmosphere, given the utilities' projected needs for

fuel in the example case where fuel needs will be met by burning oil rather than natural gas,<sup>2</sup> as shown in Table 6 and Figure 2.

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TABLE 6  
DERIVED DEMAND FOR LICENSES TO EMIT SULFUR OXIDES AIR POLLUTANTS  
AT EDISON AND DWP POWER PLANTS

Price of a license to emit a ton of SO <sub>x</sub> (dollars)	Demand by Edison (tons per day)	Demand by DWP (tons per day)	Total Demand (tons per day)
\$ 0 to \$ 210	2371	734	3105
210 to 420	1482	459	1941
420 to 470	593	184	777
470 to 940	296	92	388
940 to 2720	148	46	194
2720 to 4590	59	18	77
4590 and up	15	5	20

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Of course if we had considered intermediate sulfur contents the demand function would decrease smoothly instead of being a step function. As before, the value of demand at points of discontinuity can be the upper or lower value. Since one license represents one ton of sulfur oxides emitted into the air, the derived demand curves also yield the amount of sulfur emitted into the atmosphere annually by the utilities as a function of license price.

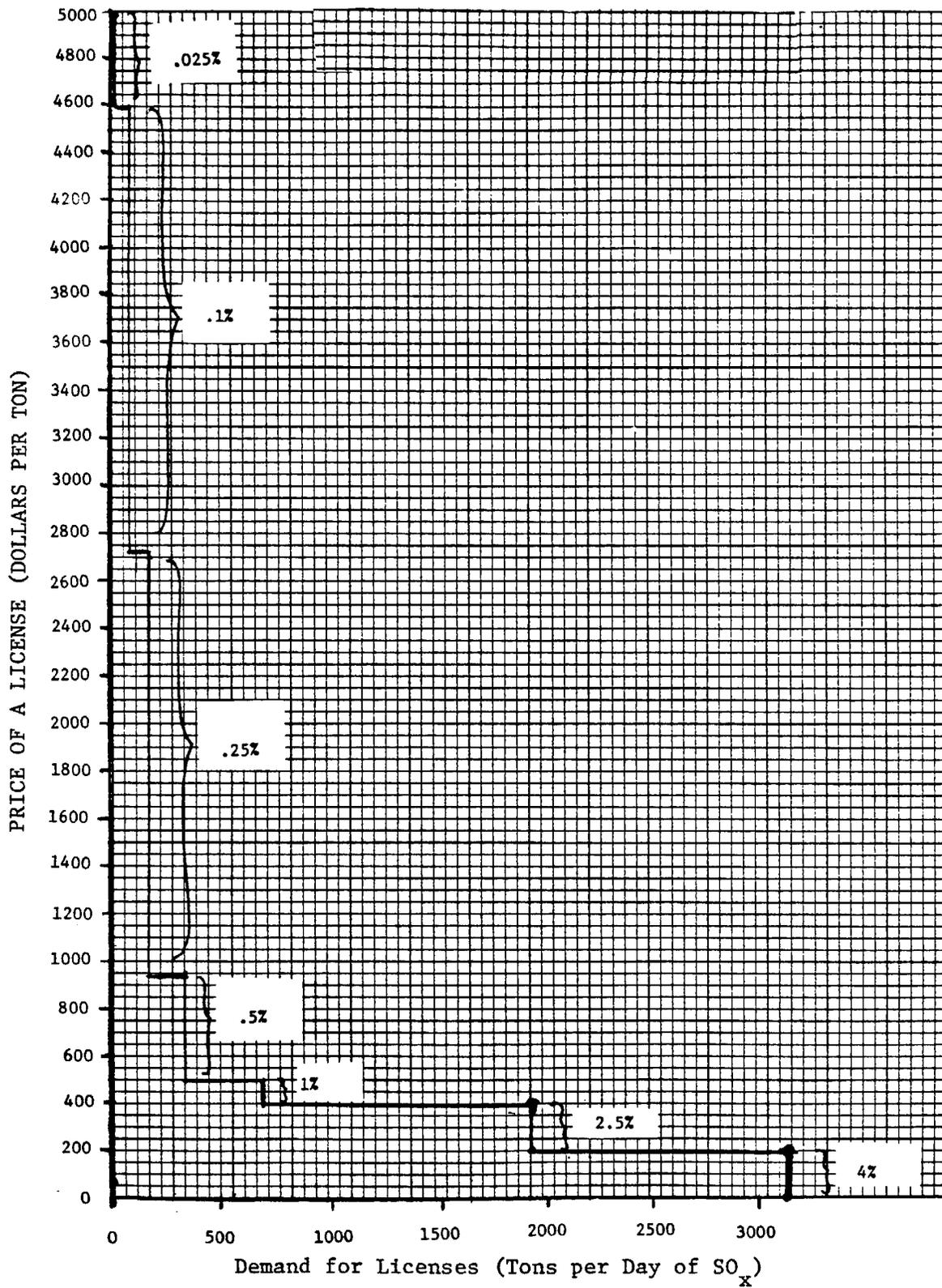


Fig. 2 Derived Demand for Licenses

## FOOTNOTES

1. The Aerospace study suggested 90 percent of the SO<sub>2</sub> would be removed. The SRI study suggested 95 percent would be removed.
  
2. In reality, some combination of gas and oil will probably be used in the early 1980s. Use of any natural gas would lower utility demand for licenses to emit sulfur oxides.

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TABLE A-1

MID-1977 PROJECTION OF 1980 ELECTRICAL GENERATION BY  
EDISON OIL FIRED STEAM PLANTS IN THE SOUTH COAST AIR BASIN

Plant	Unit	Capacity (Megawatts) (b)	Capacity Factor (c)	Estimated Electrical Production (10 <sup>6</sup> kwh/365 day year)
Alamitos	1	175	24.3	372.75
	2	175	24.3	372.75
	3	320	64.3	1,807.40
	4	320	64.3	1,807.40
	5	480	71.6	3,018.89
	6	480	71.6	3,018.89
El Segundo	1	175	24.3	372.75
	2	175	24.3	372.75
	3	335	64.3	1,892.12
	4	335	64.3	1,892.12
Etiwanda	1	132	8.5	98.56
	2	132	8.5	98.56
	3	320	64.3	1,807.40
	4	320	64.3	1,807.40
Highgrove	1	32.5	8.5	24.27
	2	32.5	8.5	24.27
	3	44.5	8.5	33.23
	4	44.5	8.5	33.23
Huntington Beach	1	215	58.6	1,106.70
	2	215	58.6	1,106.70
	3	215	58.6	1,106.70
	4	225	58.6	1,158.17
Long Beach	(a)	100	8.5	74.5
Mandalay	1	215	58.6	1,106.70
	2	215	58.6	1,106.70
Ormond Beach	1	750	69.2	4,558.90
	2	750	69.2	4,558.90
Redondo Beach	1	74	8.5	55.25
	2	74	8.5	55.25
	3	70	8.5	55.25
	4	74	8.5	55.25
	5	175	24.3	372.75
	6	175	24.3	372.75
	7	480	71.6	3,018.89
	8	480	71.6	3,018.89
San Bernardino	1	63	8.5	47.04
	2	63	8.5	47.04

## Notes:

- (a) Cluster of old units  
 (b) Reference: Southern California Edison Company (1976)  
 (c) Reference: Southern California Edison Company (June 1977)

TABLE A-2

MID-1977 PROJECTION OF 1980-81 ELECTRICAL GENERATION BY  
DWP OIL FIRED STEAM PLANTS IN THE SOUTH COAST AIR BASIN

Plant	Unit	Capacity (Megawatts)	Capacity Factor	Estimated Electricity Production (10 <sup>6</sup> kwh/365 day year)
Haynes	1	222	50.22	977.6
	2	232	67.37	1,370.3
	3	220	66.41	1,279.8
	4	227	70.43	1,398.5
	5	344	69.91	2,109.6
	6	344	77.90	2,350.5
Scattergood	1	179	31.01	485.9
	2	179	33.70	528.0
	3	309	76.14	2,060.3
Harbor	1	78.5	0	0
	2	78.5	0	0
	3	92	0.92	7.4
	4	92	2.14	17.3
	5	94	1.61	13.3
Valley	1	101	4.73	41.9
	2	101	3.27	28.9
	3	171	9.41	141.0
	4	160	29.43	412.5
Total		3,224	46.84	13,222.7

Reference: Los Angeles Department of Water and Power  
(February 7, 1977 and August 9, 1977)

TABLE A-3

1976 AVERAGE HEAT RATES FOR SOUTHERN CALIFORNIA EDISON AND  
 LOS ANGELES DEPARTMENT OF WATER AND POWER CONVENTIONAL STEAM  
 GENERATING STATIONS IN THE SOUTH COAST AIR BASIN

	1976 Actual (a) Heat Rate (BTU/kwh)	1976 Oil Burned (10 <sup>6</sup> BTU/Yr)	1976 Natural Gas (10 <sup>6</sup> BTU/Yr)	Heat Rate Adjusted (b) to All Oil Operation (BTU/kwh)
<b>Southern California Edison</b>				
Alamitos	9,868	68,197,613	8,850,727	9,830
El Segundo	10,022	30,204,169	10,354,953	9,936
Edwanda	10,101	30,862,690	9,529,807	10,020
Highgrove	13,997	383,999	287,543	13,794
Huntington Beach	9,974	21,832,079	10,374,217	9,865
Mandalay	9,815	13,351,131	4,322,416	9,734
Ormond Beach	9,754	56,764,209	1,245,721	9,747
Redondo Beach	10,235	48,373,537	9,681,465	10,177
San Bernardino	10,268	3,419,742	4,373,825	10,073
<b>Los Angeles Dept. of Water &amp; Power</b>				
Haynes	9,564	62,211,510	4,900,723	9,540
Scattergood	10,129	6,632,475	10,204,564	9,919
Harbor	12,801	393,242	922,494	12,668
Valley	11,299	3,800,348	4,271,610	11,116

Notes: (a) Heat rate: total BTU's of fuel heating value consumed  
 net kwh of electricity produced

(b) Electrical generation using oil is estimated to be 3.5% more thermally efficient than using natural gas.

References: Southern California Edison (1976)  
 Los Angeles Department of Water and Power (1976).

TABLE A-4

EARLY 1980s PROJECTED RESIDUAL FUEL OIL USE  
 BY SOUTHERN CALIFORNIA EDISON CONVENTIONAL STEAM  
 GENERATING STATIONS IN THE SOUTH COAST AIR BASIN  
 (BASE CASE: ALL FUEL NEEDS MET BY OIL)

Plant	Unit	Residual Fuel Oil Consumption, (Barrels/Year) <sup>(b)</sup>
Alamitos	1	598,608
	2	598,608
	3	2,902,550
	4	2,902,550
	5	4,848,114
	6	4,848,114
El Segundo	1	605,064
	2	605,064
	3	3,071,371
	4	3,071,371
Etiwanda	1	161,605
	2	161,605
	3	2,963,521
	4	2,963,521
Highgrove	1	54,693
	2	54,693
	3	74,885
	4	74,885
Huntington Beach	1	1,783,606
	2	1,783,606
	3	1,783,606
	4	1,866,557
Long Beach		154,183 <sup>(a)</sup>
Mandalay	1	1,759,921
	2	1,759,921
Ormond Beach	1	7,259,437
	2	7,259,437
Redondo Beach	1	91,859
	2	91,859
	3	91,859
	4	91,859
	5	619,740
	6	619,740
	7	5,019,252
	8	5,019,252
San Bernardino	1	77,410
	2	77,410
Total		67,771,336

- Notes: (a) Heat rate for the older Long Beach conventional generating units assumed to be 12,668 BTU/kwh based upon data from small, old units at the LADWP Harbor Plant.
- (b) SCE residual fuel oil energy content given as 6,121,080 BTU/bbl.

TABLE A-5

EARLY 1980s PROJECTED RESIDUAL FUEL OIL USE  
 BY LOS ANGELES DEPARTMENT OF WATER AND POWER CONVENTIONAL  
 STEAM GENERATING STATIONS IN THE SOUTH COAST AIR BASIN  
 (BASE CASE: ALL FUEL NEEDS MET BY OIL)

Plant	Unit	Residual Oil Consumption (Barrels/year)
Haynes	1	1,524,192
	2	2,136,458
	3	1,995,358
	4	2,180,425
	5	3,289,113
	6	3,664,548
Scattergood	1	787,671
	2	855,918
	3	3,339,863
Harbor	1	0
	2	0
	3	15,320
	4	35,817
	5	27,535
Valley	1	76,119
	2	52,502
	3	256,152
	4	749,381
Total		20,986,372

Notes: (a) LADWP Residual Fuel Oil energy content  
 given as 6,118,849 BTU/bbl

TABLE A-6

ESTIMATED CAPITAL COSTS OF SCRUBBER  
INSTALLATION FOR EDISON (\$/KW)

<u>Plant</u>	<u>Unit</u>	<u>SRI</u>	<u>Aerospace</u>	<u>Average</u>
Alamitos	1	140*	120.6	130.3
	2	140*	120.6	130.3
	3	146.5	120.6	133.6
	4	146.5	120.6	133.6
	5	136.4	120.6	128.5
	6	136.4	120.6	128.5
El Segundo	1	140*	161.5	150.8
	2	140*	161.5	150.8
	3	145.4	161.5	153.5
	4	145.4	161.5	153.5
Etiwanda	1	140*	143.9	142.0
	2	140*	143.9	142.0
	3	143.5	143.9	143.7
	4	143.5	143.9	143.7
Highgrove	1	140*	134.9*	137.5
	2	140*	134.9*	137.5
	3	140*	134.9*	137.5
	4	140*	134.9*	137.5
Huntington Beach	1	148.5	142.7	145.6
	2	148.5	142.7	145.6
	3	146.4	142.7	144.6
	4	146.4	142.7	144.6
Long Beach		140*	134.9*	137.5
Mandalay	1	148.5	134.9*	141.7
	2	148.5	134.9*	141.7
Ormond Beach	1	131.2	121.8	126.5
	2	131.2	121.8	126.5
Redondo Beach	1	140*	150.4	145.2
	2	140*	150.4	145.2
	3	140*	150.4	145.2
	4	140*	150.4	145.2
	5	140*	150.4	145.2
	6	140*	150.4	145.2
	7	136.4	150.4	143.4
	8	136.4	150.4	143.4
San Bernardino	1	140*	134.9*	137.5
	2	140*	134.9*	137.5

\* Cost estimates for these particular units not given in the references cited; hence the average of the estimates for all plants (DWP and Edison) was used. For SRI this figure is \$140 and for Aerospace it is \$134.9.

TABLE A-7

ESTIMATED CAPITAL COSTS OF SCRUBBER  
INSTALLATION FOR DWP (\$/KW)

<u>Plant</u>	<u>Unit</u>	<u>SRI</u>	<u>Aerospace</u>	<u>Average</u>
Harbor	1	140	134.9*	137.5
	2	140	134.9*	137.5
	3	140	134.9*	137.5
	4	140	134.9*	137.5
	5	140	134.9*	137.5
Valley	1	140	154.3	147.2
	2	140	154.3	147.2
	3	140	154.3	147.2
	4	140	154.3	147.2
Scattergood	1	140	134.9*	137.5
	2	140	134.9*	137.5
	3	140	134.9*	137.5
Haynes	1	140	117.5	128.8
	2	140	117.5	128.8
	3	140	117.5	128.8
	4	140	117.5	128.8
	5	140	117.5	128.8
	6	140	117.5	128.8

\*Aerospace did not give estimates for these plants. The average figure of \$134.9 was therefore used.

\*\*SRI did not break down its estimate for DWP by plant. It only gave an overall average for DWP of \$140/KW.

TABLE A-8  
ESTIMATED OPERATING COSTS OF SCRUBBERS  
FOR EDISON (MILLS/KWH)

<u>Plant</u>	<u>Unit</u>	<u>SRI**</u>	<u>Aerospace</u>	<u>Average</u>
Alamitos	1	2.1	1.7	1.9
	2	2.1	1.7	1.9
	3	2.1	1.7	1.9
	4	2.1	1.7	1.9
	5	2.1	1.7	1.9
	6	2.1	1.7	1.9
El Segundo	1	2.1	2.1	2.1
	2	2.1	2.1	2.1
	3	2.1	2.1	2.1
	4	2.1	2.1	2.1
Etiwanda	1	2.1	1.8	2.0
	2	2.1	1.8	2.0
	3	2.1	1.8	2.0
	4	2.1	1.8	2.0
Highgrove	1	2.1	2.0*	2.1
	2	2.1	2.0*	2.1
	3	2.1	2.0*	2.1
	4	2.1	2.0*	2.1
Huntington Beach	1	2.1	2.0	2.1
	2	2.1	2.0	2.1
	3	2.1	2.0	2.1
	4	2.1	2.0	2.1
Long Beach		2.1	2.0*	2.1
Mandalay	1	2.1	2.0*	2.1
	2	2.1	2.0*	2.1
Ormond Beach	1	2.1	1.7	1.9
	2	2.1	1.7	1.9
Redondo Beach	1	2.1	4.5	3.3
	2	2.1	4.5	3.3
	3	2.1	4.5	3.3
	4	2.1	4.5	3.3
	5	2.1	1.9	2.0
	6	2.1	1.9	2.0
	7	2.1	1.9	2.0
	8	2.1	1.9	2.0
San Bernardino	1	2.1	2.0*	2.1
	2	2.1	2.0*	2.1

\*Aerospace did not provide an estimate for this unit. Therefore the weighted average for all plants (except Redondo 1-4 and Valley) was used.

\*\*SRI provided only an average estimate for all Edison plants.

TABLE A-9

## ESTIMATED OPERATING COSTS OF SCRUBBERS FOR DWP (MILLS/KWH)

<u>Plant</u>	<u>Unit</u>	<u>SRI**</u>	<u>Aerospace</u>	<u>Average</u>
Harbor	1	2.1	2.0*	2.1
	2	2.1	2.0*	2.1
	3	2.1	2.0*	2.1
	4	2.1	2.0*	2.1
	5	2.1	2.0*	2.1
Valley	1	2.1	4.7	3.4
	2	2.1	4.7	3.4
	3	2.1	4.7	3.4
	4	2.1	4.7	3.4
Scattergood	1	2.1	2.0*	2.1
	2	2.1	2.0*	2.1
	3	2.1	2.0*	2.1
Haynes	1	2.1	1.4	1.8
	2	2.1	1.4	1.8
	3	2.1	1.4	1.8
	4	2.1	1.4	1.8
	5	2.1	1.4	1.8
	6	2.1	1.4	1.8

\*Aerospace did not provide an estimate for this unit. Therefore the weighted average for all plants (except Redondo 1-4 and Valley) was used.

\*\*SRI provided only an average estimate for all Edison plants. Therefore this figure is used.

TABLE A-10

## ESTIMATED ANNUALIZED SCRUBBING COSTS FOR EDISON

Plant	Unit	Annualized Capital Cost (Mills/kwh)	Total Annualized Cost (Mills/kwh)	Total Annualized Cost (\$ per bbl)
Alamitos	1	12.2	14.1	8.78
	2	12.2	14.1	8.78
	3	4.7	6.6	4.11
	4	4.7	6.6	4.11
	5	4.1	6.0	3.74
	6	4.1	6.0	3.74
El Segundo	1	14.2	16.3	10.04
	2	14.2	16.3	10.04
	3	5.5	7.6	4.68
	4	5.5	7.6	4.68
Etiwanda	1	38.1	40.1	24.50
	2	38.1	40.1	24.50
	3	5.1	7.1	4.34
	4	5.1	7.1	4.34
Highgrove	1	36.9	39.0	17.32
	2	36.9	39.0	17.32
	3	36.9	39.0	17.32
	4	36.9	39.0	17.32
Huntington Beach	1	5.7	7.8	4.84
	2	5.7	7.8	4.84
	3	5.6	7.8	4.84
	4	5.6	7.8	4.84
Long Beach	10	36.9	39.0	18.84
Mandalay	1	5.5	7.6	4.78
	2	5.5	7.6	4.78
Ormond Beach	1	4.2	6.1	3.83
	2	4.2	6.1	3.83
Redondo Beach	1	39.0	42.3	25.40
	2	39.0	42.3	25.40
	3	39.0	42.3	25.40
	4	39.0	42.3	25.40
	5	13.6	15.6	9.38
	6	13.6	15.6	9.38
	7	4.6	6.6	3.97
	8	4.6	6.6	3.97
San Bernardino	1	36.9	39.0	23.44
	2	36.9	39.0	23.44

TABLE A-11

ESTIMATED ANNUALIZED SCRUBBING COSTS FOR DWP

Plant	Unit	Annualized Capital Cost (Mills/kwh)	Total Annualized Cost (Mills/kwh)	Total Annualized Cost (\$ per bbl)
Harbor	1	*	*	*
	2	*	*	*
	3	341.2	343.3	165.81
	4	146.7	148.8	71.87
	5	195.0	197.1	95.20
Valley	1	71.1	74.5	40.98
	2	102.8	106.2	58.41
	3	35.7	39.1	21.51
	4	11.4	14.8	8.14
Scattergood	1	10.1	12.2	6.71
	2	9.3	11.4	7.03
	3	4.1	6.2	3.83
Haynes	1	5.9	7.7	3.94
	2	4.4	6.2	3.97
	3	4.4	6.2	3.97
	4	4.2	6.0	3.85
	5	4.2	6.0	3.85
	6	3.8	5.6	3.59

\*No electricity is produced from these units.

## APPENDIX F-2

## PETROLEUM COKE CALCINERS

Robert Hahn

This paper examines the economics of the petroleum coke calcining industry in the Los Angeles basin. The purpose is to assess the viability of the coke calciners under a market in transferable rights to emit sulfur oxides. A summary of the coke calcining process is presented in Section I along with some background material on the industry. Estimates of abatement costs, emissions and the demand for sulfur oxides emission licenses are presented in Section II. The issue of plant closure is discussed in Section III.

## I. GENERAL BACKGROUND

Almost all calciners currently used for processing petroleum coke are rotary kilns, of the type illustrated in Figure 1 (Hunter and Helgeson, 1976). Green coke is fed continuously down the rotary kiln while air and gas, injected from the bottom, pass over and through the coke. In the process, moisture is removed and volatiles are released, which are then burned to help meet the kiln's energy requirements (Foulkes and Harper, 1978). While the coke can also be used as fuel for the process, this is not allowed in Los Angeles because of the comparatively high sulfur content of the coke. Instead, either oil or natural gas is usually used.

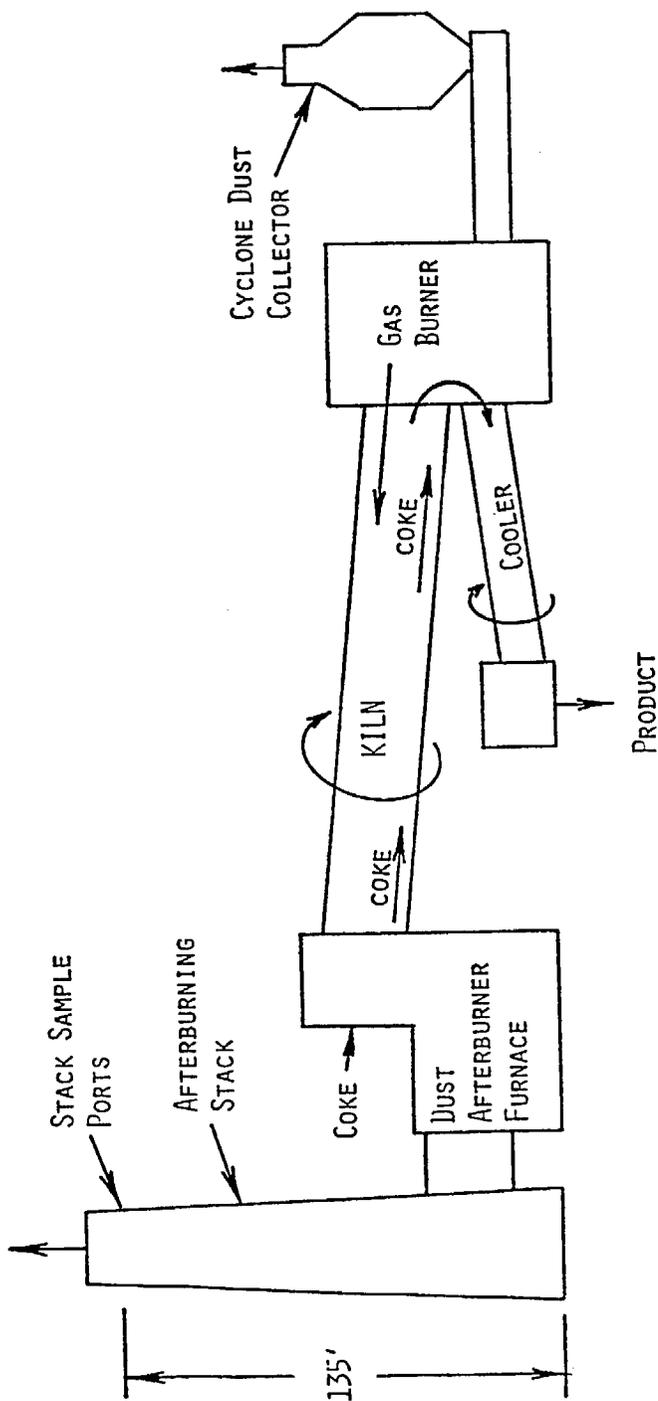


FIGURE 1. PETROLEUM COKE CALCINATING KILN SCHEMATIC.

Source: Hunter and Helgeson (1976), p. K-2.

The main source of sulfur oxides emissions ( $SO_x$ ) results from the combustion of coke dust particles, which are entrained in the air and gas passing through the system. The majority of these emissions pass through the stack; however, a small amount (equal to approximately 1 percent of the stack emissions) leave through the cyclone dust collector (Hunter and Helgeson, 1976). In addition,  $SO_x$  emissions can result from the burning of sulfur-bearing fuels, but again, such emissions are relatively small, usually comprising less than 5 percent of total  $SO_x$  emissions.

The quality of calcined coke depends on the level of impurities, such as sulfur and metals, the crystalline structure and several physical properties such as conductivity and resistance (Reis, 1975b). Traditionally, cokes with low sulfur and metallic content have been used in the production of aluminum anodes. The primary aluminum industry has been the major demander of calcined coke in the past and, according to projections of two industry participants, will remain so in the future, comprising about 75 percent of the market (Buddenberg, 1979; Foulkes and Harper, 1978).

The structure of the industry reflects the close linkages to the supplier of its inputs and its principal customer. Approximately 30 percent of United States calcining capacity is owned by divisions or subsidiaries of oil companies while 40 percent of the capacity is accounted for by end users, primarily aluminum (Buddenberg, 1979). The market shares of the four largest U.S. firms are given in Table 1.

TABLE 1  
MARKET SHARES

Great Lakes Carbon	35 %
Kaiser	15 %
Reynolds Aluminum	15 %
Union Oil Co.	10 %
4 firm concentration ratio	75 %

Source: Buddenberg (1979)

Several of the firms in the industry have established subsidiaries in other countries. The general picture that emerges is one of a highly concentrated industry with some vertical integration both backwards and forwards.

There are two firms which have petroleum coke calcining plants in the Los Angeles basin -- Great Lakes Carbon (GLC) operates a plant with three kilns in Wilmington, California, and Martin Marietta Carbon (MM) runs a plant with one kiln in Carson, California. The next section develops estimates of the effects of different pollution abatement schemes by focusing on the characteristics of the two individual plants.

## II. ABATEMENT COSTS OF PETROLEUM COKE CALCINERS IN LOS ANGELES

Ideally, it would be useful to predict how the petroleum coke calciners would fare under a decentralized market system such as an effluent fee or tradable license scheme. This requires an estimate of profits and abatement costs. Because figures on the profitability of calcining operations are unavailable, the following remarks will focus on the problem of obtaining abatement cost estimates for  $\text{SO}_x$  emissions.

There are three published studies which develop estimates for the cost per ton of  $\text{SO}_x$  or  $\text{SO}_2$  removed. The estimates are summarized in Table 2. The scrubber cost estimates are developed under very

TABLE 2  
ESTIMATE OF  $\text{SO}_x$  OR  $\text{SO}_2$  REMOVAL COST USING  
CURRENTLY AVAILABLE SCRUBBER TECHNOLOGY

<u>Source</u>	<u>GLC</u>	<u>MM</u>
Hunter and Helgeson (1976)	\$ 600/ton of $\text{SO}_x^a$	\$ 600/ton of $\text{SO}_x^a$
Leo and Rossoff (1978)	\$2447/ton of $\text{SO}_2^b$	\$1157/ton of $\text{SO}_2^b$
South Coast AQMD (1978)	\$1740/ton of $\text{SO}_2^c$	\$ 80/ton of $\text{SO}_2^c$

- a. Rough estimates presumably in 1976 dollars; these estimates do not distinguish between the two plants  
 b. in late 1977 dollars  
 c. presumably in 1978 dollars

different assumptions. The figure of \$80 per ton of  $\text{SO}_2$  reduction for MM is suspect and may be a typographical error. The most detailed documentation of cost estimates is contained in Leo and Rossoff (1978). These cost estimates are based on the objective of emitting no more than 1.5 pounds of  $\text{SO}_2$  per ton of green coke charged into the kiln, which is equivalent to about a 90% reduction in emissions using their emissions projections. To meet this level of emissions reductions, Leo and Rossoff assume that both companies will build scrubbers. This explains their relatively high figure for the average  $\text{SO}_2$  removal cost.

The abatement costs presented in the literature are of limited use because they rarely consider how costs vary as a function of emissions. Since such information is fundamental, I have developed estimates of the abatement cost curves on the basis of data from Great Lakes Carbon and Martin Marietta.

Table 3 gives the cost of reducing  $\text{SO}_x$  emissions for GLC. Currently, GLC has three baghouses in operation to remove particulates. The technology on which the Great Lakes Carbon cost estimates are based is sodium carbonate injection, which is a wet scrubbing process. Cost estimates are provided for 70 and 80 percent removal. This allows us to compute an incremental or marginal cost for removing a ton of  $\text{SO}_x$  in the 0-70 percent interval and the 70-80 percent interval. The basic approach is to divide the incremental cost by the number of tons removed. An estimate of the incremental cost is obtained by removing the items labeled "Plant Overhead" and "Contingency," and adding the first two columns in Table 3. This

yields a cost of \$2,552,000 for 70 percent removal and an incremental cost of \$513,900 for removing the next 10 percent.

TABLE 3

ESTIMATED COST OF ABATEMENT -- SUBMITTED BY  
GREAT LAKES CARBON AS PART OF TESTIMONY ON PROPOSED RULE 1119

SODIUM CARBONATE INJECTION  
(Annual Cost)

	Continuous controls		Intermittent controls	
	70%	80%	36 days	18 days
Raw material, delivered	1,288,200	1,682,400	138,020	69,010
Utilities	93,100	93,100	9,980	4,990
Manpower & benefits	180,600	180,600	19,350	9,675
Repair & Maintenance	222,100	222,100	23,800	11,900
Waste Disposal	451,100	570,800	48,330	24,165
Plant Overhead	339,800	339,800	339,800	339,800
Taxes & Insurance	50,000	50,000	50,000	50,000
Depreciation (5 years)	200,000	200,000	200,000	200,000
Supervision & benefits	66,900	66,900	66,900	66,900
SUBTOTAL	2,891,800	3,405,700	896,180	776,440
Contingency (10%)	289,200	341,000	89,620	77,640
TOTAL	3,181,000	3,746,700	985,800	854,080
\$/ton calcined coke	5.26	6.19	1.63	1.41

Source: Great Lakes Carbon Corporation (1979).

Total yearly emissions are computed by linking the rate of input with daily emissions and then multiplying by the number of days per year the plant is operating. GLC has three kilns with a capacity to produce 600 short tons per day of calcined coke (Leo and Rossoff, 1978). I assume a charge rate of 36.9 tons per hour per kiln which corresponds to a daily emissions rate of 15.24 tons of  $SO_x$  for all three kilns (Cass, 1979). Combining this emissions data with the cost data yields a marginal cost per ton of \$650 for the first 10.67 tons and \$920 for the next 1.52 tons. This information is summarized in Table 4.

TABLE 4  
MARGINAL ABATEMENT COST DATA  
(1978 \$s)

	Percent reduction in emissions	Quantity reduced (tons $SO_x$ /day)	Marginal cost (\$/ton $SO_x$ )
GLC	0- 70	0-10.67	650
	70- 80	10.67-12.19	920
	80-100	12.19-15.24	920 and up
MM	0- 33	0-2.50	0
	33- 80	2.50-6.06	1320
	80-100	6.06-7.58	1320 and up

The calculations for Martin Marietta require some further assumptions. With current equipment, MM can remove approximately 33 percent of their total  $SO_x$  emissions (Young, 1980). To remove 80 percent of their total  $SO_x$  emissions would require a capital outlay of \$5.5 million. This includes expenditure on a spray dryer scrubber system, a baghouse, and significant modifications to existing equipment (Young, 1980). Assuming a 20 percent capital recovery factor yields an annualized capital cost of \$1.1 million. Since no figures on operating costs were available, they were estimated on the basis of the Great Lakes Carbon data in Table 3. Subtracting the depreciation figure from the 80 percent removal cost estimate gives a total of \$2,865,900 or about \$640/ton. This figure is assumed to be MM's operating cost per ton for removing anywhere from 33-80 percent of the  $SO_x$  emissions.

To obtain the annual capital cost per ton of  $SO_x$  removed, an estimate of total emissions is needed. MM has a single kiln with a rated capacity of 750 tons per day (Leo and Rossoff, 1978). Assuming a 37 ton per hour charge rate, this corresponds to an average daily emissions rate of 7.58 tons of  $SO_x$  (Cass, 1979). Dividing the cost of removal by the corresponding reduction in tons results in an annualized capital cost of \$680/ton for reductions between 33 and 80 percent. Adding the operating cost yields a total incremental cost of \$1320/ton in this range. These calculations are summarized in Table 4.

It is possible to compute the derived demand for  $SO_x$  emission licenses from the marginal cost information contained in Table 4. At any given license price, a firm chooses that level of licenses which

minimizes the sum of abatement costs and license costs. The data for GLC and MM are presented in Table 5. The choice of whether to include the endpoints of the intervals in the left-hand column of the table is arbitrary.

The derived demand curves shown in Figure 2 are drawn as step functions to indicate that only a few discrete changes in abatement levels are considered. According to the graph, GLC will reduce emissions by 0, 70 or 80 percent, unless the price of a license is at a switching point. Similarly MM will reduce emissions by 33 or 80 percent. These emission reductions should not be interpreted as precise point estimates, but rather as an indication of the likely range of abatement which calciners would choose in response to a market mechanism for controlling  $SO_x$  emissions.

TABLE 5  
THE DERIVED DEMAND FOR  $SO_x$  EMISSION LICENSES

	License Price (1978 \$s)	Demand in tons $SO_x$ /day
GLC	0-650	15.24
	650-920	4.57
	920 and up	3.05
MM	0-1320	5.08
	1320 and up	1.52

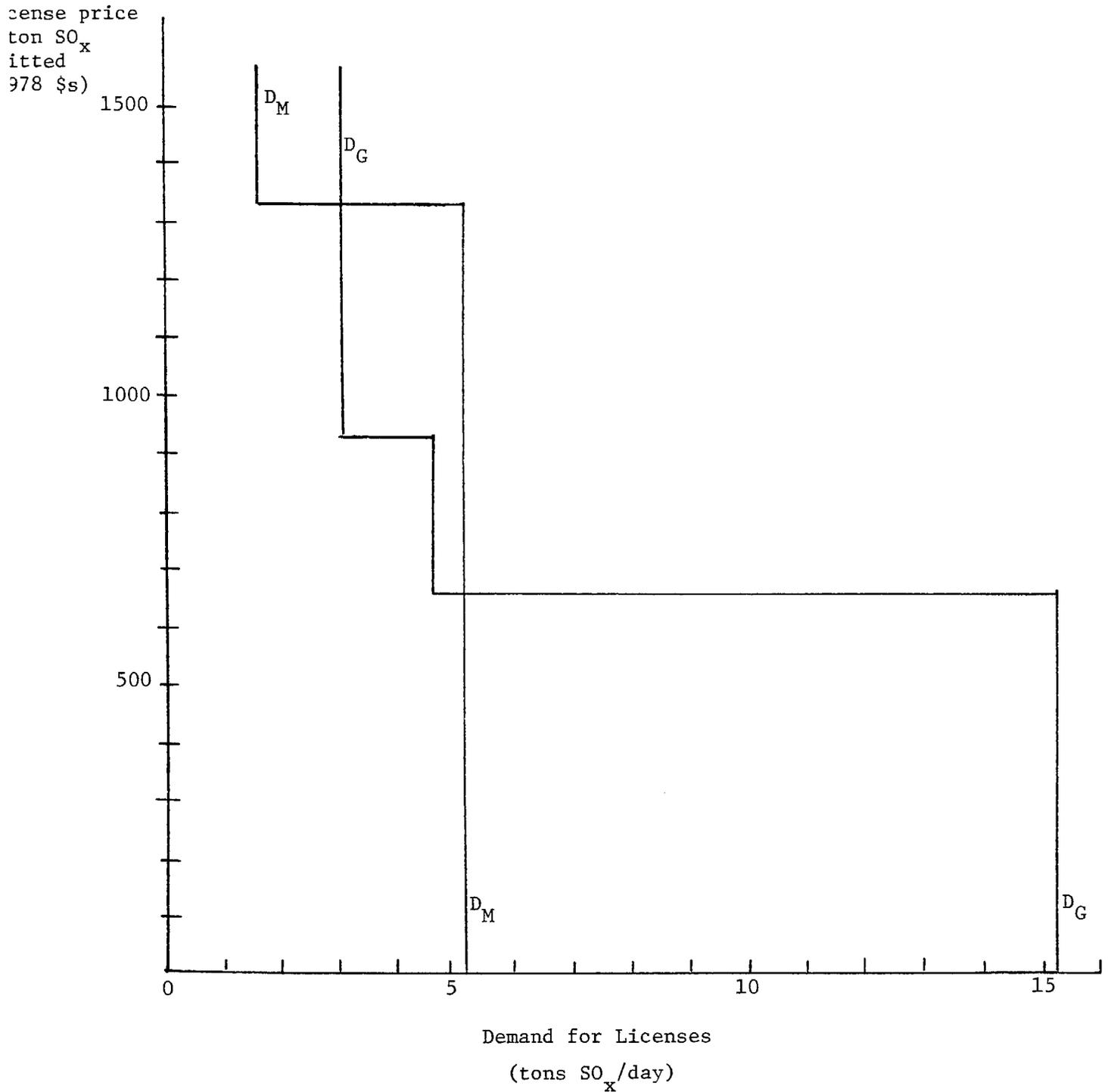


Fig. 2 Estimate of Derived Demand for SO<sub>x</sub> Emissions Licenses

D<sub>G</sub> - Derived demand for SO<sub>x</sub> emission licenses by GLC

D<sub>M</sub> - Derived demand for SO<sub>x</sub> emission licenses by MM

### III. THE POSSIBILITY OF PLANT CLOSURE

There is one important point which the analysis has left unresolved. That is the effect a market in tradable licenses would have on output decisions, and in the extreme, whether either or both of the firms would be forced to close down. If the supply price of raw coke were to remain unchanged, then the effect on output would ultimately depend on the elasticity of demand for calcined coke and the change in the supply function induced by the implementation of a market in  $SO_x$  emission licenses. Information on these parameters is unavailable; nevertheless, it may be possible to develop some educated guesses on the likelihood that these firms would be forced to close.

Plant closure would be likely to occur if the price of inputs increased significantly relative to competitors. A market in  $SO_x$  emission licenses could affect local calciner costs in two ways: first, by charging for the right to pollute and second, by affecting the price of green coke. The first effect will probably increase overall spending on  $SO_x$  abatement for both GLC and MM, but this should be compensated for by a decline in the price of green coke.

The reason for the expected drop in raw coke prices is that local petroleum refiners who supply coke would have two alternatives if local calciners shut down. The refiners could either sell the coke as fuel or sell the coke to calcining operations outside the Los Angeles basin. In the first case, losses on sales could be quite significant. According to one oil industry executive, current prices for raw coke sold to calciners range from \$20 to \$70 per ton while prices on green coke sold as fuel range from \$15 to \$40 per ton. The

coke sold for fuel is typically of lower quality than that sold to calciners. Using the above numbers it would appear that selling all green coke as fuel could result in losses on the order of \$15 to \$30 per ton of green coke. If, instead, the green coke were sold to calciners, the cost of rail transportation could be expected to exceed \$20 per ton for shipping to San Francisco and at least twice that much for shipping to calciners in the Pacific Northwest (Riske, 1980). It appears, then, that local oil companies would be willing to absorb at least a \$10 reduction in the price of green coke (per ton) before looking for other alternatives. If this is true, the likelihood that calciners would have to close would seem to be small, provided the equilibrium license price does not induce them to remove more than 80 percent of their current  $SO_x$  emissions.

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## APPENDIX F-3

## SULFUR ABATEMENT AT KAISER STEEL

by George Fox

Modern iron making is a complex chemical process involving the reduction of iron ore — oxidized elemental iron and impurities — to molten iron that is 94.15 percent pure. The two main inputs to the process, coal and iron ore, contain large amounts of sulfur; metallurgical coals typically contain from .4 to 1.2 percent sulfur by weight, iron ores from .015 to .15 percent. Hot metal must contain less than .03 percent sulfur to retain its strength and structural properties; excess sulfur leads to cracking and tearing in rolling.<sup>1</sup> In section I we will follow the flow of sulfur through a modern ironmaking facility. In so doing we will estimate the total discharge of sulfur from the Kaiser Steel plant, this being the first step in assessing the demand for sulfur oxides emission licenses should a market in licenses be implemented.

We will also discuss planned and in-place emission control equipment, as well as promising, inexpensive newer techniques for the reduction of sulfate pollution. Within this framework we will also look at process control options as they currently exist and the effects a spot market in emission licenses may have on input selection and production alteration. The steelmaking section will not be looked at in this study. Kaiser has shut down all open hearth furnaces, a large source of  $so_x$  emissions, and is currently operating the basic

oxygen plant no. 2, responsible for less than four tons SO<sub>2</sub> equivalents per year (1978 inventory). The no. 1 oxygen shop, which is currently unused due to slack steel demand, emits roughly 20 tons per year SO<sub>2</sub> equivalents.<sup>2</sup>

Section II will attempt to pick up some loose ends: the trigger price mechanism and its effect on West Coast steel markets, inland transportation as a competitive disadvantage and the very important question of Kaiser's future viability in facing an emission license market in addition to worldwide steelmaking overcapacity.

Before examining these issues, a brief history and corporate profile of Kaiser Steel will be undertaken as useful background for the analysis to follow. Kaiser's Fontana, California, iron and steelmaking facility was constructed during World War II to supply Henry J. Kaiser's shipyards with steel. Kaiser wanted to locate on the coast but the military insisted that the plant be protected from possible Japanese shelling. The inland location without access to inexpensive shipping, puts Kaiser at a distinct disadvantage. However, due to the recent closings of other mills, Kaiser is now the only fully integrated steel mill west of the Rockies. As the nation's ninth largest steel producer, Kaiser has capacity running to 3.4 million tons of finished steel.

The company owns its own iron ore mine and pelletizing plant, Eagle Mountain in Riverside County, California, 160 miles from its Fontana mill, which supplies about 2.6 million tons of ore. About 75 percent of the coal requirements are fulfilled by mines owned and leased in Sunnyside, Utah, 800 miles away, and York Canyon, near

Raton, New Mexico, 1100 miles away. All limestone requirements are satisfied through ownership in mines at Cushenbury, California, operated by Kaiser Cement and Gypsum. Proven reserves of both coal and limestone are estimated at fifty years.

Seven coke oven batteries, each containing 45 individual oven slots, with a combined capacity of nearly 1.7 million tons of coke per year, supply four ironmaking blast furnace with raw iron output over 2.6 million tons per year. Two sinter lines with a combined capacity of 3850 tons per day produce agglomerations of ore and coke fines, recycled flue dust, mill scale, scrap and limestone for use in the blast furnaces.

Under the old steelmaking technology there were twelve open hearth furnaces which are now shut down. In early October 1979, the No. 1 Basic Oxygen Furnace (BOF) shop, originally constructed in 1959, was shut down until further strengthening in steel demand. The No. 2 BOF shop, a new, computerized facility opened in 1978 as part of a \$250 million modernization program, has a capacity for 2.3 million tons of steel per year. In addition, the steel finishing section includes rolling and finishing mills, ingot stripping and soaking pits. Final good fabrication plants are operative in Napa, California as well as the main Fontana facility. Kaiser also owns marine assembly yards in Oakland and Vallejo, California, a tubing maker, formerly MSL Tube and Steel Company, in Vernon, California, and drum and pail and metal stamping facilities in California, Oregon and Arizona.

The list of final products includes steel slabs, plate, ingot molds, pig iron, coal chemicals, hot and cold rolled sheet and strip, galvanized sheet, high quality pipe for oil and gas, as well as electric resistance, submerged, high test tin mill products, large-diameter water pipe, penstocks, pressure vessels, tunnel supports and liners, and offshore exploration and drilling platforms. Kaiser fabricates and erects bridges and buildings, designs and manufactures equipment for the production of line pipe, manufactures railroad car and automotive components and other stamped products. Kaiser also owns Kaiser International Shipping Corporation, with five vessels totalling 525,000 dwt. and shipping mostly coal, crude oil, iron ore and bulk products.

Kaiser has a 32.5 percent interest in Kaiser Resources Ltd. a Canadian coal, oil and gas producer; sold in August 1979 was a 28.3 percent interest in Hamersley Holding Ltd., an Australian iron ore producer.

In past years the estimated total annual return to investors has been in the 15-30 percent range with actual growth and dividends accounting for 18 percent per year.<sup>3</sup> Current debt stands at approximately \$335 million with most in low interest mortgage obligations (\$238 million), 7 to 7 1/4 percent Pollution Control Obligations (\$33 million), and 9 percent bank loans due from 1980 to 1985 (\$40 million). Current net worth is estimated to be \$512 million for 1979. Kaiser's debt to equity of 1 to 2 is higher than the usual 1 to 4 in the steel industry but much lower than the 4 to 1 ratio found for West Coast subsidiaries of foreign firms.<sup>4</sup>

## I SULFUR FLOW AND BALANCE - CONTROL TECHNOLOGIES

There are three basic material inputs -- coal, iron ore and limestone -- that are used in the production of iron, along with an energy input, the major share from the burning of the coke oven gas (COG) arising from the conversion of coal to coke. COG provides roughly two-thirds of all plant-wide energy requirements, the rest being provided by fuel oil, natural gas and utility supplied electricity.<sup>5</sup> When natural gas was under federal regulation during the 1970s, Kaiser burned a .5 percent sulfur fuel oil; with the lifting of the regulations a switch has been made to natural gas. Into the foreseeable future supplies are expected to be plentiful. We won't consider any  $so_x$  emissions due to fuel oil inputs at this time although they can be included using the procedure developed by Rogerson.<sup>6</sup> (1980)

Sulfur content in metallurgical coal varies from .4 to 1.2 percent sulfur by weight. During the coking process, which involves the heating of coal in a refractory brick-lined slot oven, light weight hydrocarbons are driven off and collected for further processing and use. The remaining material, elemental carbon with contaminants is called coke. This product is pushed from the ovens in an incandescent state onto rail cars and cooled in a "quenching" tower to prevent the oxidation of the carbon. Roughly 1350 pounds per ton of coal is produced as coke and breeze. The volatile material driven off in the heating cycle is collected and processed for use as COG, tar, ammonium sulfate, ammonia liquid and light oil. Later in this

section we will discuss the  $so_x$  emission reduction equipment currently installed on coke ovens at Kaiser.

A coke production cost model developed by PEDCo Environmental, Inc.<sup>7</sup> seems to represent quite realistically the important aspects of coke oven operation. The variable that appears to be the most crucial in determining emission and performance relationships is the gross coking time. Information from interviews with Kaiser personnel suggest gross coking times of from 13 to 20 hours. The choice of coking time depends on a number of factors: grade, quality and price of the coal, desired properties of the final product, production level, etc. The total tonnage of coal carbonized per year depends inversely on the gross coking time; shorter gross coking times lead to higher throughput of coal to coke. Similarly, the COG yield in  $ft^3$  per ton of coal depends on the gross coking time and the percentage of volatile matter in a linear manner,

$$COG = (14,000 - 150T)(V/29)$$

where T is the gross coking time, V is the percentage of volatile matter (29% is the baseline value. The coal used by Kaiser has roughly 33 percent volatile matter.) The total coal carbonized in tons per year is given by

$$TCC = (8760)(.92)(CHARGE/OVEN)(\# \text{ of Ovens})/T$$

where an overall oven outage of 8 percent is assumed. An equation for the ammonium sulfate produced in pounds per ton of coal under a COG cleaning system is given by,

$$\text{Ammonium Sulfate Yield} = (3.53 + .741.T)(V/29)$$

Table 1 presents these figures for the Kaiser facility using gross coking times of 13, 14 and 15 hours. A study done by KVB Research Associates for the California Air Resources Board<sup>8</sup> estimated a daily COG production rate of 78 million cubic feet per day. At 78 percent capacity utilization (1975), COG at full production is roughly  $100 \times 10^6$  cf per day, in good agreement with the PEDCO value of  $100.9 \times 10^6$  cf per day. As a further check on the consistency of the available information we can estimate the underfiring heat requirements per ton of coal from the KVB data. The KVB report finds a usage rate for the underfiring of the coke ovens of 200,000 cf per hour per coke oven battery. A 13 hour underfiring (with a one hour decarbonization time for a gross coking time of 14 hours), 45 ovens per batteries, 15 tons of coal per oven, and 525 BTU's per cubic foot COG heating value yields a  $2 \times 10^6$  BTU per ton coal of underfiring requirement, in agreement with the  $1.92 \times 10^6$  BTU per ton of coal value used by PEDCO. The undesulfurized COG  $H_2S$  content can be estimated from the PEDCO data using the total recovered ammonium sulfate, corrected for the stoichiometric ratio of hydrogen sulfide to ammonium sulfate. The resulting value of 211 grains  $H_2S$  per 100cf is in good agreement with the 220 grains  $H_2S$  per 100 cf found by KVB from the sampling of the flue gas stream on Kaiser's coke ovens.

TABLE I

GROSS COKING TIME (hours)	13	14	15
TOTAL COAL CARBONIZED (Million Tons per Year)	2.93	2.72	2.54
TOTAL COKE YIELD (Million Tons per Year)	1.81	1.68	1.57
TOTAL COG (10 <sup>6</sup> Cubic Feet per Day)	110.1	100.9	81.8
TOTAL AMMONIUM SULFATE (Thousand Tons per Year)	21.9	21.5	21.2
COG H <sub>2</sub> S Content (Grains per Hundred Cubic Feet)	197	211	256

There are currently six baghouses for particulate control on the coke ovens at Kaiser; batteries F and G vent to a common stack. This arrangement is not in compliance with the current standard; bigger fans will probably be required. An earlier experiment with a TRW wet ESP scrubber was a failure due to excessive corroding. Future expenditures of roughly \$20 million will be used to upgrade doors and top seals, and emission controls for use during the pushing of the incandescent coke from the ovens to the rail car. A COG desulfurization plant of the Takahox-Hirahox<sup>9</sup> type is currently coming on line -- problems with naphthalene sublimation currently prevent full operation, but no other major problems are foreseen. The cost of the system was \$34 million, which was financed by the Pollution Control Obligation mentioned earlier.

In our calculations of emissions from the coke ovens we will use a 95 percent efficiency for the desulfurization process. It should be noted that even with the cleaning of the COG, there will still be seepage through the refractory brick oven lining so the baghouses will still be necessary for proper control. At the present time there appears to be no satisfactory way to estimate these emissions.<sup>10</sup>

After quenching, the coke is crushed and screened, the large pieces being charged directly to the blast furnace. The smaller pieces called coke breeze are combined with limestone, ore fines, dust, etc. and sintered on a travelling grate. The mixture is ignited under a hood, either with COG, blast furnace gas, or other fuel, burning from top to bottom as it travels along the grate. The

agglomerates obtained at the end are charged directly to the blast furnace in mixtures with coke, iron ore, limestone and pellets. A typical mixture designed to yield one ton of sinter contains roughly 2000 pounds iron ore, 135 pounds coke and from 100 to 350 pounds of limestone.<sup>11</sup> Return fines and losses which balance out are roughly 1000 pounds. The coke in the mixture provides 85 percent of the heat requirements for the sinter; net ignition heat requirements vary from .24 to .34 million BTUs per ton of output. Burning undesulfurized COG results in .35 pounds SO<sub>2</sub> per ton sinter; blast furnace gas or desulfurized COG results in .017 pounds SO<sub>2</sub> per ton output. In contrast the coke supplies 2.35 pounds SO<sub>2</sub> per ton sinter. By far the largest source of sulfur results from high sulfur content iron ore, over 6 pounds SO<sub>2</sub> per ton sinter, low sulfur ore being an order of magnitude smaller. With the trend to higher sulfur ores (low sulfur ores have been mined quite extensively and are at a premium price) it can be expected that sinter plant so<sub>x</sub> emissions will tend to increase. In 1975, Kaiser's sinter emissions were less than 5 tons SO<sub>2</sub> per day; by 1978 they had risen to 8 tons SO<sub>2</sub> per day (both periods had the same capacity utilization.) The KVB report published in June 1976 recorded SO<sub>2</sub> concentrations of 250 ppm in the exhausts while results from the AQMD published in May, 1978 study showed concentrations of 400 ppm.

The limestone addition value is the other determining factor in sinter plant SO<sub>x</sub> emissions. Low limestone mixtures result in three-fourths of the SO<sub>2</sub> being driven off with the stack gases.<sup>12</sup> As the limestone content is increased more of the sulfur is bound up in

the sintered product, usually half being emitted and half being retained in the sinter.

Current controls on the sinter lines consist of two, 12 year old baghouses for the control of particulate emissions. The AQMD Sulfate study<sup>13</sup> lists two techniques for SO<sub>2</sub> emission reductions on the sinter lines. The wet scrubbing method utilizes a chemical reaction between the flue gas and an alkaline scrubbing solution which results in the removal of SO<sub>2</sub> from the gas stream. Many units are presently in use in the United States, Europe and Japan. Although the method is well understood, the costs per ton of sulfur reduced are high, in the neighborhood of \$2000 per ton of SO<sub>2</sub>. A method known as dry caustic injection,<sup>14</sup> although still experimental, seems to blend better into the system at Kaiser. A dry caustic powder, usually sodium bicarbonate, is crushed and ground then used to coat the baghouse bags. Further amounts are injected into the exhaust gas stream to combine with SO<sub>2</sub> to form sodium sulfate. This is collected in the baghouse and then disposed of in the same manner as slag from the blast furnace. Cost savings can be realized through the pre-existence of the baghouse and slag disposal accommodations. Annual capital costs for crushing, screening, and injection equipment run about \$600,000 per year, nahcolite ore -- which is mined nearby and 75 percent sodium bicarbonate -- sells at \$30 per ton, yielding costs of \$775,000 per year. A reduction of 3500 tons SO<sub>2</sub> per year results in a cost of \$400 per ton of SO<sub>2</sub> reduced.<sup>15</sup>

The final stage of iron production is nearly continuous. A mixture of iron-bearing inputs -- ore, sinter and pellets -- is mixed

with coke and limestone and charged into the top of the blast furnace. Blasts of superheated air are blown into the bottom of the furnace. The incomplete burning of the coke yields carbon monoxide which forms with oxygen in the ore to reduce the iron in the charge. The hot metal collects in the bottom to be drawn off to the steel furnaces. The limestone combines with impurities in the charge and floats on top of the metal as slag. Slag can also be drawn off and new raw materials can be periodically charged to the furnace. The proper composition of the charge is a very complicated problem: heat balance to get the proper reduction of the iron ore, and sulfur accounting to keep the hot metal sulfur content below .03 percent.<sup>16</sup>

Off gases from the blast furnace are well-controlled at Kaiser. With current equipment the sulfur content is roughly 9 grains per 100 cf, well within regulations. Emissions can however occur during the slag flush. Indications are that usually 15 percent of the sulfur in the slag is released to the air.<sup>17</sup> The final emissions can depend on the amount of sulfur in the slag as well as the amount of water in contact with the slag when flushed. Blast furnace emissions have increased from a little over one ton per day in 1975 to over four tons per day in 1978, primarily due to a move to higher sulfur ores. These emissions are largely uncontrollable. Fortunately the Fontana location is quite dry so that the expected emissions are much less than would be found in the same plant in a wetter location.

A hot metal desulfurization technique using a calcium carbide process is also installed. The SCAQMD seems satisfied that there is no excess release of sulfur. Its use is purely for metal quality and

not for airborne emission reduction.<sup>18</sup>

A wide range of variability can be seen in total  $so_x$  emissions. Changes in sulfur contents in the inputs as well as process control changes can have major effects on total airborne  $SO_2$ /sulfates released. The final section attempts to put these effects together to come up with a realistic emissions picture. In the next section we will discuss points relevant to  $so_x$  emission licenses outside the generation and control technologies at the plant level.

## II EXTERNAL FACTORS

An analysis of final product markets is important in determining the impact of a system of emission license markets. If the firm has a large degree of market control then emission costs can be passed through to the consumers of the final goods. Steel demand tends to be cyclical; as the business cycle swings up demand for steel also rises, as recessionary phases are entered demand falls off. Estimating a demand for emission licenses tends to be complicated when final output rises and falls substantially. One smoothing effect on final demands is the trigger price mechanism<sup>19</sup> originally designed to prevent the dumping of foreign steel. Under the mechanism, to the unit cost of steel from Japan -- the assumed lowest cost producer -- is added currency corrections and transportation costs to arrive at a trigger price. If foreign concerns are selling at less than the trigger price to U.S. customers, then an antidumping suit is filed. The effect is that foreign firms selling in the U.S. will keep their

prices above the trigger price in fear of an antidumping suit. In times of high demand when all firms are raising prices there is no effect; however in times of slack demand, foreign firms will not be able to go below the trigger price, hence domestic firms will pick up the demand. This may help to increase the market power of domestic firms.

The effects on the fertilizer market in Southern California from the added production of ammonium sulfate at the Kaiser facility will also be important. Using information from the Annual Survey of Manufactures published by the U.S. Department of Commerce<sup>20</sup> a very rough estimate of 60,000 tons per year of fertilizer consumed in the Southern California Market can be made. The 20,000 tons per year from Kaiser could make a sizeable penetration into the market. The PEDCo study assumes a \$65 per ton of ammonium sulfate credit. This figure could conceivably be reduced substantially, perhaps as low as \$30 per ton due to market influences. Russell and Vaughan give a figure in 1968 dollars of \$17 per ton. Under the previous coke oven cleaning technology, Kaiser had losses of roughly \$200 per ton of ammonium sulfate at low production rates. With the new desulfurization equipment at the same price per ton of ammonium sulfate it costs \$600 per ton. The change in revenues from \$65 to \$35 per ton ammonium sulfate is small compared to the total costs of \$600 per ton.

The future viability of Kaiser steel is an important question. With the current lack of demand and world-wide steel overcapacity the outlook is not good. Labor costs at Kaiser have averaged 66 cents per hour higher than the industry average.<sup>21</sup> Iron ore and coal transport

costs are \$20 per ton higher than elsewhere. Add to that the already high amount spent on current controls and it's not hard to imagine further hardship should an emissions license market be implemented. On a brighter note these are all sunk costs so that should Kaiser go under and be forced to sell the facility in all likelihood it would continue to be operated.

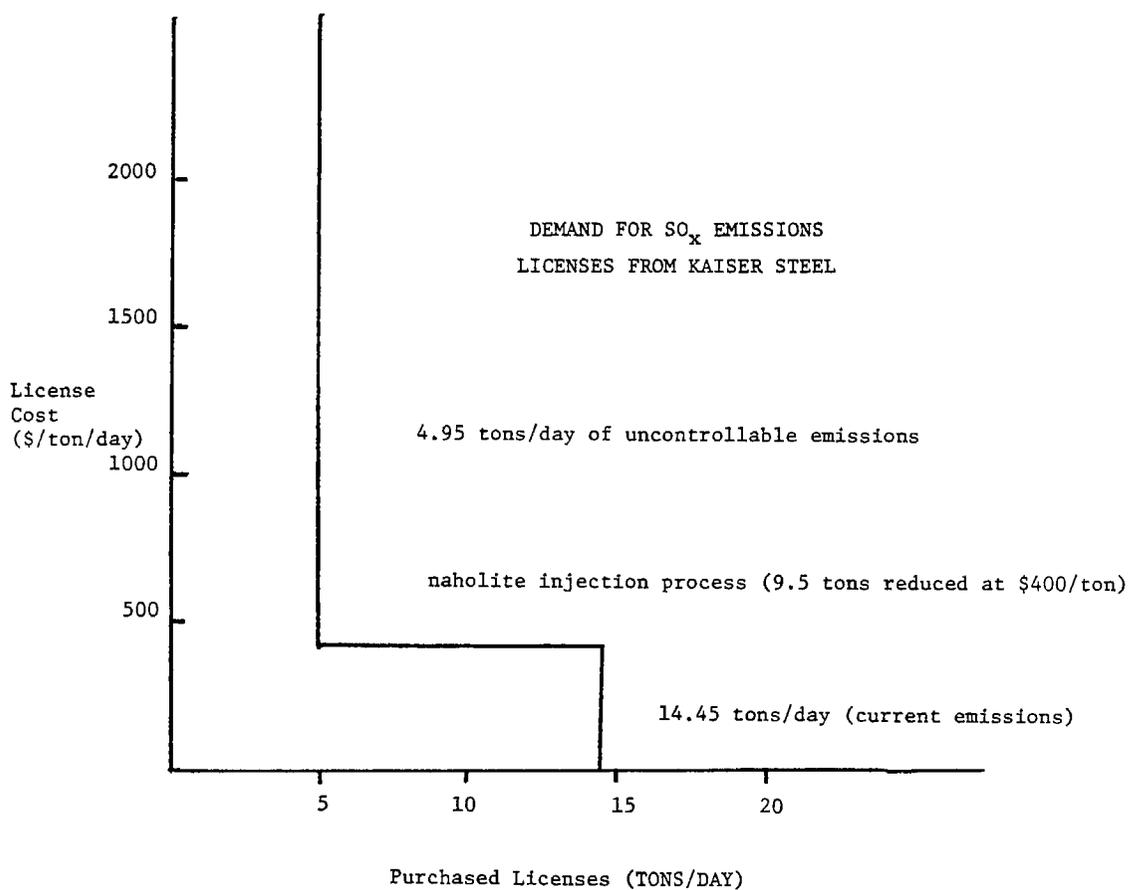
### III DEMAND FOR LICENSES

The demand for licenses is computed as follows. Emissions from the three major sources, coke ovens, sinter lines and blast furnaces are estimated, then summed to yield total emissions at full capacity. We then use a capacity utilization factor of 85 percent to compute the average total emissions.<sup>22</sup>

From the total ammonium sulfate yield of 20,500 tons per year at 95 percent efficiency, we can compute net SO<sub>2</sub> emissions after control of 1.4 tons per day. A calculation based on 1000 pounds of coke (.9% sulfur) per ton hot metal produced, a 5 percent SO<sub>2</sub> loss from the slag, and a 7200 tons per day production rate yields SO<sub>2</sub> emissions of 3.2 tons per day from the blast furnaces. The coke and ignition fuels used in sintering yield 2.6 pounds SO<sub>2</sub> per ton sinter, mainly from sulfur in the coke, and six pounds SO<sub>2</sub> per ton sinter from the use of high sulfur ore. Under the assumption of a 75 percent airborne emissions factor and a 3850 tons per day production rate, we compute SO<sub>2</sub> emissions of 12.4 tons per day. All totalled we have 17.0 tons per day SO<sub>2</sub> at full capacity or 14.45 tons SO<sub>2</sub> per day at average capacity utilization. Ninety percent reduction of sinter

emissions at \$400 per ton yields reducible emissions of 9.5 tons per day. Emissions of 4.95 tons per day of  $\text{SO}_2$  remain to be offset through the purchase of emission licenses.

It needs to be stressed again that these are very rough approximations. Any changes in average sulfur content of coal or iron ore can change  $\text{SO}_2$  emissions quite substantially. Fluctuations in the demand for final steel goods can also have an appreciable effect on total emissions. Once an emissions license market is implemented, process control options may become attractive measures of reducing emissions;  $\text{SO}_2$  prices become factors in the linear programs used by steel companies to optimize inputs and outputs. As an example, changes in blast furnace burden limestone content drastically affects airborne  $\text{SO}_2$  emissions from the slag; a similar effect takes place in the sintering process.



## FOOTNOTES

1. Russell and Vaughan gives an excellent introductory discussion of steel and iron-making processes. Any deeper incursion can be made through the references. Input sulfur contents are roughly the high and low concentration found in representative samples. The upper limit on hot metal sulfur concentration is discussed in McGannon p. 431. The McGannon reference is the steelman's bible--a detailed and complete presentation of all equipment and processes in iron and steelmaking and fabrication.
2. The 1978 Inventory of Emissions for Kaiser Steel Corporation, the most recent available estimate of emissions from Kaiser, was provided by the South Coast Air Quality Management District in Colton, California.
3. The financial information was found in the investment survey's published by Moody, Value Line, and Standard and Poors.
4. U.S. Trade Commission Report, p. 27, 126.
5. McGannan gives average plant usage figures and discussions.
6. Rogerson paper in these reports to ARB.
7. The Pedco report uses a large sample of current U. S. steel plant coke ovens and non-steel plant ovens to estimate parameters in the production cost model. The Kaiser coke

- oven characteristics are included in the PedCo study data.
8. Hunter and Helgeson used actual measurements taken on the coke ovens at Kaiser. The readings were taken in 1976.
  9. The Massey and Dunlap reference gives a survey of current coke oven gas cleaning systems and their economics.
  10. These emissions are a small fraction of total emissions at the current time and hence little effort has been expended to estimate them.
  11. Russell and Vaughan, p. 71.
  12. Russell and Vaughan, p. 72.
  13. Wet Scrubbing, pp. 6.42 ff. Dry Caustic Injection, pp. 6.61 ff.
  14. Genco, et al. is the standard reference for dry caustic injection applied to SO<sub>2</sub> emission control. The cost figure used by the SCAQMD Sulfur Dioxide/Sulfate Study are derived from those in Genco, et al.
  15. SCAQMD Study, p. 6.69.
  16. Russell and Vaughan, p. 86ff.
  17. Russell and Vaughan, p. 92.
  18. Private conversations with SCAQMD and Kaiser Steel.
  19. U. S. Internation Trade Commission, p. 75ff. A detailed

explanation of the TPM and its effects on West Coast Steel markets are discussed. There's a brief reference on page 83, to Kaiser using the TPM to discount selected flat-rolled products by utilizing the TPM "to maintain a margin beneficial to producer sales."

20. The Survey only gives dollar volumes of selected products sold in specific years in the Southern California region. Using an average wholesale price of nitrogen based fertilizer of \$25 per ton and total sales of roughly \$1.5 million in 1972 in Southern California we obtained the 60,000 ton figure.
21. L.A. Times Article, September 7, 1980.
22. Standard and Poor's investment survey gives raw iron output figures for the past decade, a good approximation for the average capacity utilization factor.

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## APPENDIX F-4

THE ECONOMICS OF SULFUR OXIDE ABATEMENT STRATEGIES  
IN GLASS MANUFACTURING

Asha Paranjape

In assessing the prospects for the use of tradable emissions rights as an approach to controlling  $\text{SO}_x$  emissions in Los Angeles, the consequences for the glass industry are an especially germane part of the analysis. Glass manufacturing is not a particularly important source of  $\text{SO}_x$  emissions, accounting for only about two tons per day  $\text{SO}_2$  equivalent, nor is it a major component of the Los Angeles economy. Interest in the industry arises because it raises some classic regulatory problems. First, the industry is comprised of several small firms, and so the issue arises that a general environmental policy that is primarily aimed at a few large sources of emissions could inadvertently drive these small businesses out of the local market. Second, the industry emits several pollutants, and control strategies for one often affect the costs and available strategies for controlling others. This chapter seeks to shed some light on these and related matters, and to develop a method for undertaking small business impact analysis that could be applied to other industries and for other emissions.

## THE INDUSTRY

Glass is a mixture of inorganic oxides and fluxes which are heated to form a solution, and then cooled sufficiently rapidly to prevent crystalization. The main component is silica,  $\text{SiO}_2$ , ordinary

sand. The fluxing agents, which affect the melting point, working temperature, viscosity and color of the mixture are added in varying proportions to achieve the desired properties in the batch.

The process, shown in Figure 1, begins by measuring the ingredients, by weight, according to the batch formula, and conveying the materials to the grinder. Here they are ground for about five minutes, to facilitate the formation of the solution, and then the mixture is fed into the furnace. In large-scale production of glass, a continuous furnace is employed, which is a massive tank, constructed from refractory blocks, that has two sections. The sections are separated by a partial wall of refractory blocks that does not quite extend to the bottom of the tank, so as to permit a flow under it. The dry raw materials enter the melting end of the tank where they are raised to a temperature of around 2800°F (Phillips, 1960). At such a high temperature massive convection currents are created which serve to homogenize the mixture and permit trapped gases to escape. The mixture is initially very foamy and lumpy, but by the time it passes under the wall to the working end of the furnace, it is a clear solution. The temperature in this end of the furnace is much cooler, so that the molten glass has the right viscosity for formation.

The batch leaves the furnace through a small opening at the bottom of the extreme end of the working end of the furnace. Then it enters the automatic feeder which drops gobs of glass in the pregreased molds where they are blown or pressed. Finally, the formed containers move along a conveyor belt through the annealing ovens where they are heated again and then cooled in a regulated fashion to remove any

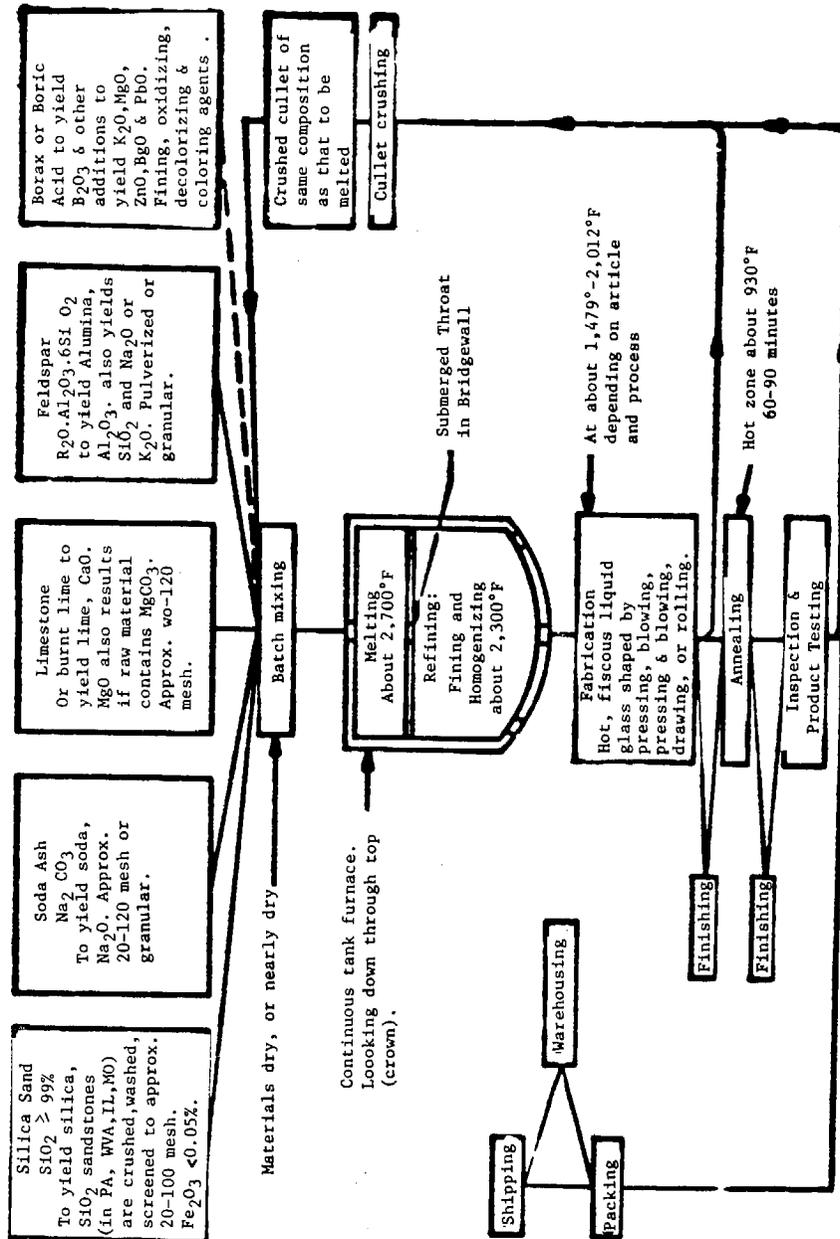


Fig. 1 Flow Diagram for Soda-Lime Glass Manufacture

stress caused by the forming.

There are twenty-six glass furnaces in the Los Angeles Basin at thirteen locations. Altogether, they produce around 2,000 tons of glass per day (a very rough approximation<sup>1</sup>) and release approximately two tons of sulfur oxides daily into the atmosphere (Cass, 1977). The significant part of the production occurs in eight large factories: Ball, Kerr, Brockway, Owens-Illinois at two locations, Glass Containers, Anchor-Hocking, and Thatcher. The rest are very minor producers. However, the situation is not as competitive as one might suspect. Many firms specialize in particular product lines (such as open-mouthed containers for packaging peanut butter), in which only two or three other firms are engaged. Buyers typically purchase from at least two or three firms, not only to get a good price, but also to guarantee themselves a steady supply since glass furnaces are usually down for about two weeks of the year.

Demand for glass grows at about 8 percent per year, and this is linked with the population growth of the basin. There are many substitutes for glass containers, such as plastic and aluminum; however, because of its clarity, purity and the property that it has no effect on the taste, glass will definitely remain an important means of packaging foods and beverages. Furthermore, although no exact numbers can be quoted, the demand is quite inelastic with respect to prices.<sup>2</sup>

On the supply side, it is more difficult to say what the elasticity is. At present glass producers do not have any genuine excess capacity; the furnaces are generally running at their normal

load, unless they are down because of malfunctions (which tend to occur fairly frequently), and can be run harder for unexpected surges in demand, although this practice has a serious adverse effect on the furnace. A furnace can normally operate five to six years between renovations, but this period, called the campaign, can be halved by overuse. In extreme situations, manufacturers ship from their San Francisco plants. The practice is that the glass producer must absorb the transportation costs when the product is not produced at the local plant.<sup>3</sup> Most producers have filed applications to expand their capacity and are awaiting the word of the authorities. Their production is growing about 2-3 percent per year (which is slower than the demand growth), and in the short run the supply is not very elastic. The long run, of course, is not really in the hands of the producers; it depends on entry and exit of manufacturing firms as well as changes in existing facilities which are greatly influenced by future environmental regulation policies.

At present, according to an interview,<sup>4</sup> most furnaces in the basin are quite old. The industry has failed to reinvest, possibly due to new source regulations. Many furnaces are due for rebricking in the early 1980s; however, the rest of the structure of the furnace lasts for about fifty years. Renovation causes a plant to come under new source review regulations when rebricking costs exceed 50 percent of the costs of total replacement. Because the rate of technological progress in a well-established industry, such as glass, is very slow, small improvements in technology are not sufficient incentive to replace existing furnaces, and low profit furnaces (7-8 percent return on total investment) are being run. Newer designs have been adopted for the few new facilities

that have been approved by the environmental authorities.

## SO<sub>2</sub> EMISSIONS

In the Los Angeles Basin, the dominant line of production is soda-lime glass, for containers and clear beverage bottles. The ingredients of the soda-lime glass are 70-74 percent SiO<sub>2</sub>, 13-16 percent Na<sub>2</sub>O and K<sub>2</sub>O, 10-13 percent CaO and MgO, 1.5-2.5 percent Al<sub>2</sub>O<sub>3</sub>, and 0-0.5 percent BaO (Phillips, 1960). These can be gotten from sand, soda ash, salt cake, limestone, potash, dolomite, feldspar and barium carbonate. The main sources of sulfur are salt cake, Na<sub>2</sub>SO<sub>4</sub>, impurities in the sand, and the sulfur content of any fuels used. Other particulates can be formed during the reactions in the melting end and can be liberated from the batch by the bubbling hot gases. The emissions from the batch are the major source of pollution from glass factories. We shall not consider other sources, such as emissions from burning fuel, which are minor, dust arising from the grinding and moving of dry materials, which can be prevented by sealing the whole operation, and the burning of lubricants in the molds, a problem which has been resolved with a new lubricant consisting almost entirely of water.

A curious feature of glass production is that the amount of sulfur oxides emitted varies widely from furnace to furnace. It depends largely on the particular condition of the furnace. The size and temperature of the smelter area influences the emissions since this is where the air comes in contact with the molten chemicals and reacts to form sulfur oxides. Another very important factor is the sulfur content of the batch ingredients themselves. The condition of the

regenerative furnaces also affects the emissions. By a regenerative furnace we mean that the exhaust gases are used to heat up a checkerwork of refractory blocks. Every fifteen to twenty minutes the intake and the outflow stacks are reversed, so that the heated blocks will heat the incoming air and the combustion in the furnace will be more efficient. However, as the dirty air passes through the checkerwork, dust collects on the surfaces which forms slag, and drips down to the lower passages. In later stages, the clogging of the checkers may be so severe that many passages are blocked off. Often the state of the checkers will determine which pollutants are emitted to the atmosphere. But of course, as the passages get worse, the efficiency of the furnace falls and more sulfur-containing fuel has to be burned to keep the production going. Destructive forces set in as hot spots develop in the clogged checkers and air is still being forced through the passages until complete breakdown occurs. There are access doors to the various checkerwork chambers that permit some periodic cleanup, but it can never be complete. The checkers do eventually deteriorate and require at least partial rebuilding every five to six years. Thus, removal of the slag-forming pollutants is consistent with the interests of the glass producers. It will reduce maintenance costs as well as increase the campaign of the furnace, and it may also reduce fuel costs.

At present there are three general environmental regulations of the South Coast Air Quality Management District that affect the glass industry: Rule 401, an opacity limit; Rule 405, limiting particulate matter concentration in the stack; and Rule 406, limiting the weight of

particulate matter emitted from the furnace. Because the latter two have become progressively stronger, the opacity constraint is no longer binding. Sulfur oxides emission controls have not been applied directly to glass furnaces to date in the Los Angeles area. The industry is anticipating a ruling on NO<sub>x</sub> emissions which would become effective in the next year or two.

Environmental control agencies normally seek adoption of the best available control technology (BACT). This approach has certain problems. Presumably regulatory agencies seek to meet a specified air quality objective using a control strategy that minimizes interference with the rest of the economy. The actual policy is far more simple than this idea would imply, being to identify the BACT, and to announce that a source will be subject to continuing pressure from the agency until it is adopted. Two immediate questions arise.<sup>5</sup> First, are the agencies able to even find a best control technology, given that they are not engaged in the production activity that they are trying to regulate? Second, even if they do, how do they know it is best for every producer? Each glass furnace is different, and industry-wide BACT standards do not take these factors into account.

An additional problem is that, over time, regulatory policy sometimes overlooks compatibility issues. The BACT for one pollutant does not necessarily function very well in conjunction with the BACT for another. So those who succumbed to persuasion to reduce one emission last year can find themselves regretting not having left their options open. It is not a matter of irresponsibility, but a problem of uncertainty: uncertainty about which pollutants will become the dominant problems in the future, and how various political forces will work to form the new rules.

Table 1 (Tanner, 1975) shows that sulfur oxides are emitted from glass furnaces both as  $\text{SO}_2$  gas and in the form of particulate matter. Thus our discussion of sulfur oxides abatement possibilities must consider control of both gaseous and particulate emissions. The two known means of controlling sulfur oxides emissions from glass furnaces are process modification and add-on devices.

TABLE 1

SULFUR MATERIALS BALANCE DATA ON A GLASS FURNACE  
AS REPORTED BY TANNER (1975)  
(ALL VALUES IN EQUIVALENT LB/HR  $\text{SO}_2$ )

Sulfur Input		
From Batch		64.8 LB/HR $\text{SO}_2$ Equivalents
From Cullet		2.4
From Fuel (Natural Gas)		<u>3.0</u>
	Total	70.2 LB/HR $\text{SO}_2$ Equivalents
Sulfur Retention		10.9 LB/HR $\text{SO}_2$ Equivalents
$\text{SO}_x$ Emission		
As $\text{Na}_2\text{SO}_4$		2.3
As $\text{H}_2\text{SO}_4$		1.4
As $\text{SO}_2$ (By Difference)		55.4 LB/HR $\text{SO}_2$
Measured $\text{SO}_x$		= 58.4 LB/HR $\text{SO}_2$ Equivalents

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Process modification refers to any change in the process which will reduce emissions. An obvious method is to minimize the

sulfur content of the batch by using fluxing agents that do not contain sulfur. This procedure has met with limited success since changes in the fluxing agents tend to affect the properties of the glass. Akin to minimization of the sulfur content is the procedure of adding other chemicals to the batch which prevent the formation and liberation of sulfur-bearing particles. For example, the introduction of appropriate amounts of carbon to the batch can reduce particulate emissions by at least a factor of two (Tanner, 1975). Particle emissions can further be controlled by leaving the raw materials in a coarser mixture so that the escaping gases from the batch carry with them less dust from the raw materials. Another technique of reduction of sulfur oxides is to alter the fuel/air ratio so that the oxidation of sulfur is inhibited. Incidentally, this is also effective in reducing nitrogen oxide emissions. Some of the sulfur oxides are formed right on the melting surface where the hot batch ingredients come in contact with the air. One way to reduce this reaction is by keeping the surface area of the smelter as small as possible within certain bounds that are necessary for the production of good glass. Lastly, the temperature of the surface can be reduced, slowing down the sulfur reactions, by electric melting or just electric boosting, from within the tanks.

Unfortunately, it was not possible to obtain specific information about these process modifications and about their costs except for the electric melting. Since the research in these areas is only in the developmental stages, the firms were reluctant to reveal anything in case it could benefit their competitors. It does not

appear that these techniques have large fixed costs associated with them, with the exception of electric melting, and it was understood from the interviews that many of these methods could actually increase the efficiency of production.

The other approach to reducing sulfur oxides emissions is the use of add-on devices. There are basically three kinds of add-on devices: precipitators, scrubbers, and baghouses. Electrostatic precipitators operate by passing the flue gases between charged collection plates. They are unable to remove the acid gases although they are very efficient for removing sulfur-bearing particulate emissions. Low energy scrubbers can be used for both particulate and SO<sub>2</sub> removal provided that chemicals are added which react with the SO<sub>2</sub> and cause it to be incorporated into the scrubbing liquid. An example of this type of scrubber, which will be considered in this study, is the "nucleator," a dual alkali scrubber with regeneration of sodium-based chemicals. Also available are venturi scrubbers. These high energy scrubbers can be used with chemical reagents to remove sulfur-bearing particulate matter and SO<sub>2</sub>. Venturi scrubbers have the disadvantage of high operating costs because they require a large pressure drop in the system. Lastly, the baghouse is a large fabric filter through which treated or untreated exhaust gases are passed to remove pollutants. Here the temperature of the stack gases is critical since the bags are likely to burn at high temperatures. Two kinds of baghouse systems will be considered: the "chromatographic," which concentrates on removing particulate emissions; and the "chromatographic X," which has an additional caustic injection feature designed

to react with  $\text{SO}_2$  and incorporate it into the aerosol phase for subsequent collection in the baghouse. In all cases there can be waste sludge from which useful chemicals might be recovered.

Table 2 (Teller, 1976) compares the costs and properties of five add-on devices and electric melting. Interviews with people in the industry indicate that costs have undoubtedly changed since 1976. One firm producing  $200 \pm 50$  tons per day reported the following updated 1979 costs: for the precipitator, \$500,000 capital costs and \$120,000 annual operating costs; for the scrubber, \$600,000 and \$175,000; and for the baghouse, \$400,000 and \$150,000, respectively. Another producing 400 tons per day was able to give the figures for the scrubber only at \$1,000,000 and \$200,000. Thus, costs appear to have changed only slightly.

From the data it appears that the chromatographic X baghouse is the least expensive and will remove 89 percent of the sulfur oxides emissions. For further reductions, 96 percent, the nucleator must be employed. At a slightly higher cost the venturi scrubber can be used to attain approximately the same results. The rest of the add-on devices and the electric melting are clearly more costly than the chromatographic X baghouse and the scrubbers. For the purpose of this comparison, sulfur-bearing particulate emissions have been converted into  $\text{SO}_2$  equivalents and then the amount of sulfur oxides abated is calculated by a weighted average of  $\text{SO}_2$  gas abated and particulate sulfur oxides abated, using for weights the proportion each type comprises of the total sulfur oxides emissions expressed in  $\text{SO}_2$  equivalents.

Present costs are not the only consideration in choosing an add-on device. The glass manufacturers understand that once purchased,

TABLE 2

## SYSTEM COMPARISON 150-TON FURNACE

	Electrostatic Precipitator	Chromato- graphic	Chromato- graphic X	Venturi	Nucleator	Electric Melt
<b>PERFORM- ANCE</b>						
Opacity	<10	0	0	<10	<10	<20
Steam Plume	No	No	No	Yes	No	No
Particulate gr/scf	0.015 0.020	0.003— 0.006	0.003— 0.006	0.015— 0.025	0.015— 0.025	0.015— 0.025
SO <sub>x</sub> Removal — %	0	~25	80-95	90-98	95-99	0
<b>CAPI- TAL</b>						
Installed Capital Cost — \$	700,000	400,000*	400,000*	550,000	550,000	Not. est.
<b>CHARACTER- ISTICS</b>						
Solid Prod — lb/hr	26	132	131	84	82	0
Compatibility	Yes	Yes	Yes	No	No	Yes
Δp in. w.g.						
Battery Limits	2	8	8	35	15	0
Installed HP	25	60	60	250	160	0
Electrical kwh/ton	0.3	0	0	0	0	950
Steam lb/ton	0	0	0	0	160	0
<b>COSTS</b>						
Costs \$/ton for *						
Emission Control						
Utilities (1)	0.20	0.14	0.14	0.57	0.43	8.50
Amortization (2)	1.30	0.74	0.74	1.02	1.02	Not Rep.
Maintenance (3)	0.51	0.26	0.26	0.56	0.62	Not Rep.
Chemicals (4)	0.00	0.06	0.14	0.23	0.11	0.00
Added Op. Labor (5)	0.07	0.14	0.14	0.28	0.28	0.00
Solids Reuse or Disp. (6)	0.01	0.05	0.05	0.03	0.03	0.00
<b>TOTAL *</b>						
Additional Cost over Fossil Fuel	2.09	1.39	1.47	2.69	2.49	\$8.50 + Amort. + Maint.
Recoverable Chem. (7)	0.04	0.06	0.15	0.15	0.15	\$8.50 + Amort. + Maint.
<b>NET COST *</b>	2.05	1.33	1.32	2.54	2.34	

\*In multiple furnace installations

(1) Utilities — Fossil fuel \$1.05/10<sup>6</sup>BTU  
Electricity \$0.02/kwh  
Steam \$0.60/1000 lb.

(2) Amortization — 10 yr. straight line

(3) Maintenance — Electrostatic — 5% Chromatographic — 3%  
Wet Systems — 6%(4) Chemicals — NaOH \$100/ton  
Ca(OH)<sub>2</sub> \$25/ton  
TESISORB A \$50/ton  
TESISORB X \$28/ton

(5) Labor — \$15,000/man year

(6) Solids Reuse or  
Disposal Cost — \$5/ton

(7) Recovery Value — \$20/ton

For consistency throughout the report the capital cost is amortized with a 20 percent capital recovery factor. Thus the costs used in this report are as follows:

Costs \$/ton for*	2.60	1.48	1.48	2.04	2.04	Not Rep.
Amortization						
TOTAL*	3.39	2.13	2.21	3.71	3.51	\$8.50 + Amort. + Maint.
Additional Cost over Fossil Fuel						
NET COST*	3.35	2.07	2.06	3.56	4.53	\$8.50 + Amort. + Maint.

\*All costs are in dollars per ton of glass produced.

they are locked in to one particular add-on device for a few years. They must be able to forecast what other pollutants will be restricted and whether their equipment will be able to handle it. Just five years ago (1974) opacity was the major source of concern. Because of the possibility of unanticipated additional rules, firms must choose a technology that is sufficiently flexible to be adaptable to the new rules. The present source of concern to glass producers is the impending  $\text{NO}_x$  rule. Because the technology for compliance with this rule has not yet been discovered, it could prove incompatible with technology for  $\text{SO}_x$  removal.

#### RELOCATION POTENTIAL

The last alternative available to the firm is to shut down its Los Angeles operation and perhaps open or expand a factory elsewhere. A plant outside the basin is attractive if the add-on device costs could be avoided, either because the regulations in that district are less stringent or because a new plant could be built to be less polluting with much lower costs than add-ons to existing facilities. There are other considerations when choosing locations, such as a sufficiently large labor market and the proper infrastructure conducive to industry.

The crucial factor in determining whether outside firms are competitive is the transportation cost of shipping raw materials to the plants and moving the finished products to the Los Angeles market. First we will discuss how transportation costs are computed for raw materials and for finished glass. Then two important questions will

be addressed: can existing glass plants located in San Francisco supply Los Angeles customers in a competitive market if the Northern California firms do not face emissions control constraints? Secondly, can a new glass plant be built closer to Los Angeles than San Francisco with transportation costs into the basin lower than the pollution abatement costs imposed on local firms?

In order to compute the cost of raw materials we need a formula for glass. The various ingredients will have different transportation costs. The idea is to add up the different transportation costs of the raw materials in such a fashion that we find the cost of shipping enough materials to produce one ton of glass. The composition of soda-lime glass for containers (Phillips, 1960) is 71-73 percent  $\text{SiO}_2$ , 13-16 percent  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ , 10-13 percent  $\text{CaO}$  and  $\text{MgO}$ , 0.5-1.5 percent  $\text{Al}_2\text{O}_3$  and 0-0.5 percent  $\text{BaO}$ . But this is not the required formula yet. The usual raw materials of glass (sand, soda ash, limestone, and fluxing agents) contain these glass-making oxides in varying proportions. Table 3 (Phillips, 1960) shows the raw materials used in soda-lime glass and the percentage of glass-making oxide each contains. It should be noticed that there is not one unique way to combine raw materials to get the right proportion of glass-making oxides. Different firms use different formulas and all firms are very secretive about the formula they use. We shall assume that the batch consists of sand, soda ash and limestone alone, and attempt to compensate for trace amounts of missing chemicals. The procedure is described fully in a footnote.<sup>6</sup> It turns out that .73 tons of sand, .273 tons of soda ash and .232 tons of limestone are needed. Fortunately, all materials are

TABLE 3

Raw Material	Chemical Formula	Oxides	Percent Oxides
Sand	$\text{SiO}_2$	$\text{SiO}_2$	100.0
Soda Ash	$\text{Na}_2\text{CO}_3$	$\text{Na}_2\text{O}$	58.5
Salt Cake	$\text{Na}_2\text{SO}_4$	$\text{Na}_2\text{O}$	44.0
Limestone	$\text{CaCO}_3$	$\text{CaO}$	56.0
Feldspar	$\text{K}_2(\text{Na}_2)\text{O} \cdot \text{Al}_2\text{O}_3$ $\cdot 6\text{SiO}_2$	$\text{SiO}_2$	68.0
		$\text{Al}_2\text{O}_3$	18.0
		$\text{K}_2(\text{Na}_2)\text{O}$	13.0
Dolomite	$\text{CaCO}_3 \cdot \text{MgCO}_3$	$\text{CaO}$	30.4
		$\text{MgO}$	21.8
Potash	$\text{K}_2\text{CO}_3 \cdot 1.5\text{H}_2\text{O}$	$\text{K}_2\text{O}$	57.0

found at the same location, in the neighborhood of Carlsbad, which is 86 terrain and traffic-adjusted miles from Los Angeles. Using Table 4 and other PUC rates, the cost to transport the raw materials necessary for producing a ton of glass to Los Angeles from the Carlsbad area is between \$9.73 and \$13.26.

The nearest location to Los Angeles of other glass producing facilities is San Francisco. Assuming that these plants find their raw materials from elsewhere at approximately the same cost as those in Los Angeles, competition will emerge when the abatement costs just balance the transportation of finished products from San Francisco. From the PUC shipping rate schedule, Table 5, the transportation cost works out to \$21.40 per ton of glass, which exceeds  $SO_x$  abatement costs. Thus, the existing environmental regulations are not likely to stimulate competition from outside the Los Angeles basin, but future regulation could change the picture.

As shown in Table 5, the farther the finished produces are moved, the less expensive it is per mile. So if a firm wishes to locate outside the basin, locating right at the source of the raw materials would minimize transportation costs. Thus, the minimum cost of shipping finished glass products to Los Angeles is in the range of \$10 to \$13 per ton of glass (depending on the volume of shipments).

Because these costs are approximately the same as the additional costs of production in Los Angeles (incurring the abatement costs and the costs of bringing the raw materials to Los Angeles), in the short run glass producers are not expected to move their facilities outside the basin. The fixed costs of setting up new factories would prevent

TABLE 4

ITEM	SECTION 2—DISTANCE RATES (Continued) In Cents Per Ton							
	COMMODITIES, as described in List A of Item 20, subject to Note 1. Sand, Gravel, Stone, etc.							
	MILES		RATES		MILES		RATES	
	Over	But Not Over	(1) Northern Territory	(2) Minimum Weight 24 Tons (3) Southern Territory	Over	But Not Over	(1) Northern Territory	(2) Minimum Weight 24 Tons (3) Southern Territory
0290	0	1	41	52	30	31	264	303
	1	2	49	61	31	32	271	310
	2	3	57	70	32	33	278	318
	3	4	65	79	33	34	283	325
	4	5	73	88	34	35	291	333
	5	6	81	97	35	36	298	341
	6	7	89	106	36	37	305	348
	7	8	97	115	37	38	312	356
	8	9	105	124	38	39	319	364
	9	10	113	133	39	40	325	372
	10	11	121	141	40	41	332	380
	11	12	128	150	41	42	339	387
	12	13	136	158	42	43	346	395
	13	14	143	167	43	44	353	402
	14	15	151	175	44	45	359	410
	15	16	158	183	45	46	366	418
	16	17	165	191	46	47	373	425
	17	18	172	199	47	48	380	433
	18	19	179	208	48	49	387	440
	19	20	187	216	49	50	394	448
	20	21	194	224	50	52	407	462
	21	22	201	232	52	54	419	476
	22	23	208	241	54	56	432	491
	23	24	215	249	56	58	445	505
	24	25	223	257	58	60	458	519
	25	26	230	265	60	63	473	540
	26	27	237	272	63	66	493	562
	27	28	244	280	66	69	513	583
	28	29	251	287	69	72	533	605
29	30	257	295	72	75	553	626	
(Continued)								
(1) The minimum weight must be transported in one unit of dump truck equipment at one time. (2) Subject to Item 270. (3) See Item 160 for descriptions of Northern and Southern Territories.								
NOTE 1.—Rates on decomposed granite alternate with the rates in Section 16 of Minimum Rate Tariff 17-A from Production Areas 19-EE, 19-Q, 19-QA, 19-QB, 19-R and 19-Z.								
◊ Increase, Decision No.								
EFFECTIVE NOV 1 1979								
ISSUED BY THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA, SAN FRANCISCO, CALIFORNIA.								
Correction								

TABLE 4 (continued)

SECTION 2--DISTANCE RATES (Continued) In Cents Per Ton				ITEM
COMMODITIES, as described in List A of Item 30, subject to Note 1. Sand, Gravel, Stone, etc.				
MILES		RATES		
Over	But Not Over	(1) (2) MINIMUM WEIGHT 24 TONS		290
		Northern Territory (See Item 160)	Southern Territory (See Item 160)	
75	80	584	660	
80	85	614	694	
85	90	645	728	
90	95	676	762	
95	100	707	796	
100	110	768	864	
110	120	830	932	
120	130	891	1000	
130	140	953	1068	
140	150	1014	1136	
150	160	1075	1204	
160	170	1137	1272	
170	180	1199	1340	
180	190	1261	1408	
190	200	1323	1475	
200	210	1384	1543	
210	220	1446	1611	
220	230	1508	1679	
230	240	1570	1747	
240	250	1632	1814	
250	260	1693	1882	
260	270	1755	1950	
270	280	1817	2018	
280	290	1879	2086	
290	300	1941	2154	
(3)		66	72	
(Concluded)				
(1) The minimum weight must be transported in one unit of dump truck equipment at one time. (2) Subject to Item 270. (3) For each additional 10 miles or fraction thereof, add to the rate for 300 miles the amount shown opposite this reference.  NOTE 1.--Rates on decomposed granite alternate with the rates in Section 16 of Minimum Rate Tariff 17-A from Production Areas 19-EE, 19-Q, 19-QA, 19-QB, 19-R and 19-Z.				
c Increase, Decision No.				
EFFECTIVE				
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Correction				

TABLE 5

SHIPPING RATES FOR FINISHED GLASS

SECTION 3--COMMODITY RATES (Continued)				ITEM	
In Cents Per 100 Pounds					
Multiply by 20 to get ¢ per ton					
(Numbers within parentheses immediately following commodities shown below refer to such commodities as they are described in the corresponding item numbers of the Governing Classification.)					
GLASSWARE: Bottles, Carboys, Demijohns or Jars, NOI, (87700), other than cut, with or without their equipment of caps, covers, stoppers or tops, one gallon or less in capacity, each in fibre or wicker cover in boxes or crates, or in bottle carriers with partitions with or without covers, or in barrels, boxes or crates without tops, or with tops, or in fibreboard boxes with tops not fastened, or loose, braced in vehicle.					
MILES		RATES (Subject to Notes 1 through 7)			
Over	But Not Over	Minimum Weight (In Pounds)			
		30,000	35,000	40,000	45,000
0	3	28	25	23	22
3	5	30	27	25	24
5	10	32	29	27	26
10	15	34	31	29	28
15	20	36	33	31	30
20	25	38	35	33	32
25	30	40	37	35	34
30	35	42	39	37	35
35	40	45	42	40	38
40	45	48	45	43	41
45	50	51	48	45	43
50	60	54	51	48	45
60	70	58	55	52	49
70	80	62	59	56	53
80	90	65	61	57	54
90	100	67	62	58	55
100	110	69	64	60	57
110	120	71	66	62	59
120	130	73	68	64	61
130	140	75	70	66	62
140	150			68	64
150	160			70	66
160	170			72	68
170	180			74	70
180	190			76	72
190	200			78	74
200	220			82	78
220	240			85	81
240	260			88	84
260	280			91	87
280	300			94	90
300	325			100	96
325	350			104	99
350	375			107	102
375	400			110	105

\*6643

(Continued on following page)

\* Addition )  
 & Reduction ) Decision No. 89921

EFFECTIVE MARCH 10, 1979

ISSUED BY THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA,  
 SAN FRANCISCO, CALIFORNIA.

TABLE 5 (continued)

SECTION 3--COMMODITY RATES (Continued)				ITEM	
In Cents Per 100 Pounds					
Multiply by 20 to get ¢ per ton					
(Numbers within parentheses immediately following commodities shown below refer to such commodities as they are described in the corresponding item numbers of the Governing Classification.)					
GLASSWARE: Bottles, Carboys, Demijohns or Jars, NOI, (87700), other than cut, with or without their equipment of caps, covers, stoppers or tops, one gallon or less in capacity, each in fibre or wicker cover in boxes or crates, or in bottle carriers with partitions with or without covers, or in barrels, boxes or crates without tops, or with tops, or in fibreboard boxes with tops not fastened, or loose, braced in vehicle.					
MILES		FATES (Subject to Notes 1 through 7)			
Over	But Not Over	Minimum Weight (In Pounds)			
		30,000	35,000	40,000	45,000
400	425			112	109
425	450			116	113
450	475				118
475	500				123
500	525				128
					134
525	550				140
550	575				146
575	600				
For distances over 600 miles add for each 25 miles or fraction thereof in excess of 600 miles:					6
NOTE 1.--Not subject to surcharges in effect as of the effective date of this tariff page.					*8643 (Concluded)
NOTE 2.--Shipments shall be loaded by consignor and unloaded by consignee with power equipment, furnished and used without expense to the carrier. In such circumstances, physical assistance of the carrier's employee is restricted to work within or on carrier's equipment and does not include stacking, unstacking, removal or placement of merchandise on pallets.					
NOTE 3.--Shipments may also include extra caps, covers, stoppers, tops or extra fibreboard boxes, KD flat or folded flat, not to exceed 10 percent of total weight upon which charges are assessed.					
NOTE 4.--Empty pallets used to transport commodities named in this item may be returned via the carrier handling the inbound shipment at the 35,000 pound rate named in this item subject to actual weight of pallets. Where no 35,000 pound rate is provided, the 45,000 pound rate shall be applied.					
NOTE 5.--Rates named in this item shall not be used in combination with any other rates.					
NOTE 6.--Rates herein apply per load. Load means freight transported at one time in one unit of carrier's equipment.					
NOTE 7.--An allowance of two (2) hours free time for loading and two (2) hours free time for unloading shall be made in connection with each unit of carrier's equipment used. Excess loading or unloading time will be charged for at rates in Item 145 of this tariff. Time shall be computed from shipper designated time of arrival of carrier's equipment at place of loading or unloading until loading or unloading is completed and carrier's equipment is released. If carrier arrives late for scheduled loading or unloading, free time shall begin when actual loading or unloading commences.					
* Addition ) ø Reduction ) Decision No. 89921					
EFFECTIVE MARCH 10, 1979					
ISSUED BY THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA, SAN FRANCISCO, CALIFORNIA.					
Correction 3588					

TABLE 5 (continued)

SECTION 3--COMMODITY RATES (Continued) In Cents Per 100 Pounds Multiply by 20 to get c per ton			ITEM
(Number within parentheses immediately following commodities shown below refer to such commodities as they are described in the corresponding item numbers of the Governing Classification.)			
GLASSWARE: Bottles, Carboys, Demijohns or jars, NOI (87700), other than cut, with or without their equipment of caps, covers, stoppers or tops, one gallon or less in capacity, each in fibre or wicker cover in boxes or crates, or in bottle carriers with partitions with or without covers, or in barrels, boxes or crates without tops, or with tops, or in fibreboard boxes with tops not fastened, or loose, braced in vehicle.			
BETWEEN		AND	
SAN FRANCISCO BAY AREA METROPOLITAN Zone Groups		LOS ANGELES AREA METROPOLITAN Zone Groups	
SACRAMENTO EXTENDED AREA			
NORTH SACRAMENTO EXTENDED AREA			
RATES (Subject to Notes 1 through 8)			
Minimum Weight 35,000 Pounds	Minimum Weight 40,000 Pounds	Minimum Weight 45,000 Pounds	
116	107	102	
<p>NOTE 1.--Not subject to surcharges in effect as of the effective date of this tariff page.</p> <p>NOTE 2.--Shipments shall be loaded by consignor and unloaded by consignee with power equipment, furnished and used without expense to the carrier. In such circumstances, physical assistance of the carrier's employee is restricted to work within or on carrier's equipment and does not include stacking, unstacking, removal or placement of merchandise on pallets. *6646</p> <p>NOTE 3.--Shipments may also include extra caps, covers, stoppers, tops or extra fibreboard boxes, KD flat or folded flat, not to exceed 10 percent of total weight upon which charges are assessed.</p> <p>NOTE 4.--If charges accruing under the rates in this item, applied from, to or between points intermediate between origin and destination territories via routes shown in Items 900 and 900-1 are lower than charges accruing under the Distance Rates in Item 643 on the same shipment via the same route, such lower charges shall apply. For the purpose of this item only Saugus shall be deemed to be an intermediate point between the named territories via Routes 1, 2, 3, 4, 5, 7, 15 and 19 shown in Items 900 and 900-1.</p> <p>NOTE 5.--Empty pallets used to transport commodities named in this item may be returned via the carrier handling the inbound shipment at the 35,000 pound rate named in this item subject to actual weight of pallets.</p> <p>NOTE 6.--Rates named in this item shall not be used in combination with any other rates.</p> <p>NOTE 7.--Rates herein apply per load. Load means freight transported at one time in one unit of carrier's equipment.</p> <p>NOTE 8.--An allowance of two (2) hours free time for loading and two (2) hours free time for unloading shall be made in connection with each unit of carrier's equipment used. Excess loading or unloading time will be charged for at rates in Items 145 of this tariff. Time shall be computed from shipper designated time of arrival of carrier's equipment at place of loading or unloading until loading or unloading is completed and carrier's equipment is released. If carrier arrives late for scheduled loading and unloading, free time shall begin when actual loading or unloading commences.</p>			
<p>* Addition )                  &amp; Reduction ) Decision No. 89921</p>			
EFFECTIVE MARCH 10, 1979			
ISSUED BY THE PUBLIC UTILITIES COMMISSION OF THE STATE OF CALIFORNIA, SAN FRANCISCO, CALIFORNIA.			
Correction 3589			

this alternative.

These transportation costs are higher than the cost of sulfur oxides abatement alone but this may change when  $\text{NO}_x$  regulations become effective. In addition, relocation decisions involve assessing the opportunity costs of abandoning the furnace at the present location. Because glass factories are quite specialized, they have little value in alternative uses, and they have long, useful lives. Thus, the sunk costs in Los Angeles operations are likely to be an important element in a relocation decision.

Even though the glass manufacturers seem very confident that they will be able to pass on all costs to the buyers, we should calculate how much they are earning per ton to decide whether it would be a serious problem. One producer revealed that his sales are approximately \$35 million per year, and he produces 400 tons per day. Allowing him the same average net earnings to net sales ratio as his competitors, his net earnings per ton of glass are \$8.77.<sup>6</sup> If he is required to use an add-on device, he will spend at least one-sixth of his earnings on abatement. The assumption of buyer insensitivity to price increases is probably justified, because an increase in costs of \$13.42 per ton means only a .084¢ change in the price of a beer bottle (if it weighs 2 oz.), or a .503¢ change in the price of a six-pack.

In conclusion, stronger air pollution rules will indeed be a problem for the glass producer, but they are unlikely to disrupt the local industry in the short run. The combined effect of  $\text{NO}_x$  regulations and the requirement to adopt add-on devices for sulfur

oxides emissions abatement may eventually cause more glass containers to be brought in from outside producers as the industry in the basin slowly exits.

In the presence of a licensing scheme, the likely result would be one of two events. One is less abatement by this industry and no incentive to relocate. This is because the market value of a license to emit sulfur oxides is expected to be lower than abatement costs in this industry, which in turn reflects the fact that other industries appear to face lower abatement costs per ton of emissions. The second possible result is abatement through process modification techniques, if these are substantially less expensive than add-on devices. In any case, we would expect the glass producers in the Basin to be quite secure under a license scheme. Of course, neither result is likely under a BACT regulatory scheme which tends to overlook process modifications (in part because firms do not like to reveal them for competitive reasons) and which does not recognize interplant differences in abatement costs.

## DERIVED DEMAND FOR LICENSES TO EMIT SULFUR OXIDES

The derived demand for licenses to emit  $SO_x$  is calculated from the abatement cost function. For any given license price, a firm will abate up to the point at which the marginal cost of abatement equals the price of a license. Thus, to calculate the demand for licenses requires estimating the marginal cost of abatement.

In Table 2 the performance of each add on device is measured in two ways: First, it tells us how much particulate in grains per standard cubic foot (gr/scf) remain in the stack after the device has been implemented (Line #1 of text). Second it tells us the percent removal of  $SO_2$  by each device (Line 2).

. The first step toward calculating the marginal cost (MC) of abatement curve is to arrive at an average overall control number for each device (this will be a percentage). In order to do this we will need to find out the percentage control of particulates and  $SO_2$  by each device and weigh those two numbers according to the ratios at which they are emitted. Lines 1 and 3 of Table 6 contain a range of numbers for each device. The midpoint of the range will be used to estimate the mean MC curve (to get the others, we use the end points of the range). Line 2 is the mean of Line 1, and Line 4 is the average of Line 3. Line 4 is not expressed as a percentage control but as average particulate in gr/scf in the stack. The base level of particle emission (emissions when no devices are used) is .02-.3 gr/scf (Teller 1976) or an average of 0.165 gr/scf. Using .165 gr/scf is the average amount in the stack without controls, each amount in line 4 is expressed as a percent of .165 gr/scf in line 5, which is

TABLE 6  
DERIVING MARGINAL ABATEMENT COSTS

Line	Performance Measure	Elect. Precip.	Chromat.	Chromat. X	Venturi	Nucleator	Electric Melt
1	SO <sub>2</sub> removal %	0	~ 25	80-95	90-98	95-99	0
2	Average SO <sub>2</sub> %	0	25	87.5	94	97	0
3	Particulate gr/scf	0.015-0.020	0.003-0.006	0.003-0.006	0.015-0.025	0.015-0.025	0.015-0.025
4	Avg. gr/scf.	0.0175	0.0045	0.0045	0.02	0.02	0.02
5	% particles left	10.6	2.7	2.7	12.1	12.1	12.1
6	% removed	89.4	97.3	97.3	87.9	87.9	87.9
7	Overall Average Control %	16.1	38.0	89.3	92.9	95.4	15.8
8	Weighted Average of SO <sub>x</sub> removed lbs/T of glass	.36	.86	2.01	2.09	2.15	.36
9	Total Cost/Ton	3.39	2.13	2.21	3.71	3.51	8.50 + Amort. + Maint.
10	Net Cost/Ton	3.35	2.07	2.06	3.56	3.36	8.50 + Amort. + Maint.
11	Total Cost/Ton SO <sub>x</sub> \$	18,833.33	4,953.49	2,199.00	3,550.24	3,265.12	>47,222.22
12	Net Cost/Ton SO <sub>x</sub> \$	18,611.11	4,813.95	2,049.75	3,406.70	3,125.58	>47,222.22
13	Industry Emissions tons/day	1.68	1.24	0.21	0.14	0.09	1.68

	Performance Measure	No Abatement	Chromat. X	Nucleator	Tri-Mer
14	Total Cost in \$	0	3936.21	6236.38	10405.42
15	Change in Cost in \$	0	3936.21	2300.17	4169.04
16	Abatement (SO <sub>x</sub> removed) in tons SO <sub>x</sub>	0	1.79	1.91	2.00
17	Change in Abatement in tons SO <sub>x</sub>	0	1.79	.12	.09
18	Ratio of Change in Cost/Ton to to Change in Abatement	0	2199.00	19,168.08	46,322.67

Note: Terms defined in text.

the average percent of particles still remaining in the stack when each device is used. Finally, if line 5 is subtracted from 100 percent, the result is line 6, which is the average percent of particles removed by each device.

Now it remains to weigh line 6 and line 2, in an appropriate fashion. Of the two tons per day of emissions of  $\text{SO}_x$  as  $\text{SO}_2$  equivalents, 1.64 T are  $\text{SO}_2$  gas and .36 T are  $\text{SO}_4^{=}$  as  $\text{SO}_2$  equivalents (Cass 1977). Thus, using these weights to find a single number which reflects the average effectiveness of each technology for both particles and gases, we get line 7:  $\text{line 7} = [(\text{line 2} \times 1.64) + (\text{line 6} \times .36)]/2$ . In order to determine how much sulfur is removed per ton of glass we use the fact that 0.1-4.2 lbs of  $\text{SO}_x$  are emitted per ton of glass for an uncontrolled furnace or an average of 2.25 lbs. Multiplying line 7 by 2.25 yields line 8. The reason we need this information is that all the cost figures are expressed in dollars per ton of glass.

Now let us look at the cost side. Lines 9 and 10 show the gross and net costs of each device. Net cost means net of revenue from sale of recovered chemicals. Since both costs are similar, without loss of generality, we will deal only with the gross cost.

Notice that line 9 is the cost per ton of glass and line 8 is the pounds of  $\text{SO}_x$  in  $\text{SO}_2$  equivalents removed per ton of glass. Therefore, the cost of removing a ton of  $\text{SO}_x$  can be calculated, and is shown in line 11:  $\text{line 11} = \text{line 8} \times (2000 \text{ lbs } \text{SO}_x / \text{T of } \text{SO}_x) \div \text{line 8}$ . Line 12 is a similar computation for the net costs. Line 13, calculated as  $(100\% - \text{line 7}) \times 2 \text{ T/day}$ , gives us industry emissions

if the whole industry were using that device. What we have achieved so far, is the average cost of  $\text{SO}_x$  removal.

Industry-wide emissions are the tons of sulfur oxides emitted when the whole industry used each technology. In Graph 1, the total costs have been plotted (a graph of the net costs would look similar). Two additional data have been added to the graph: the cost of moving to San Francisco and the cost of a new  $\text{NO}_x$  scrubber by the Tri-Mer Corporation. Both of these alternatives reduce sulfur oxide emissions to zero. The Tri-Mer scrubber for a 150 ton furnace has a capital cost of approximately \$800,000 (in 1980 dollars), which includes the equipment and all installation and transportation charges and an operating and maintenance cost of \$50,000 to \$100,000 per year.<sup>7</sup>

In Graph 2, all the dominated options have been excluded, and error bounds have been indicated for the mean average total cost curve. The average net costs have not been plotted since it is not clear that the glass producers will always be able to sell the chemicals recovered.

From these average cost curves, we can complete the marginal cost curves which are the derived demand for licenses, since a producer will be willing to pay for a license at most as much as it costs him to abate at the margin. In order to compute the marginal cost curve we first need the total cost curve. In this analysis only the undominated alternatives will be considered, since they are the only ones a glass producer will use. By multiplying the cost per ton of  $\text{SO}_x$  with the tons  $\text{SO}_x$  controlled, we get the total cost of each device.

In order to get the total costs we start with line 11

(costs/ton of  $SO_x$ ) and multiply by (2T - line 13), which would be the tons of  $SO_x$  removed by each device if the whole industry were using test device. This yields line 14, the dollars, with the alternatives listed in order of increasing effectiveness. Line 15 is the change in cost from moving to each alternative from the option that is next most effective. Line 16 is the tons  $SO_x$  removed by each device (if the whole industry were using that device), which is two tons less than line 13. Line 14 is the change in abatement from switching from one device to the next. Finally line 18 is the marginal cost,  $\frac{\text{Line 16}}{\text{Line 18}} = \frac{\Delta C}{\Delta A}$ . Thus, Graph 3 shows the expected choice of strategies for alternative ranges of the price of licenses in dollars for a ton per day of emissions: This is the average derived demand curve. The range of variation is computed similarly by using the variation in the average cost curves, and is shown in Graphs 2 and 4.

TABLE 7  
ABATEMENT CHOICE FOR ALTERNATIVE LICENSE PRICES

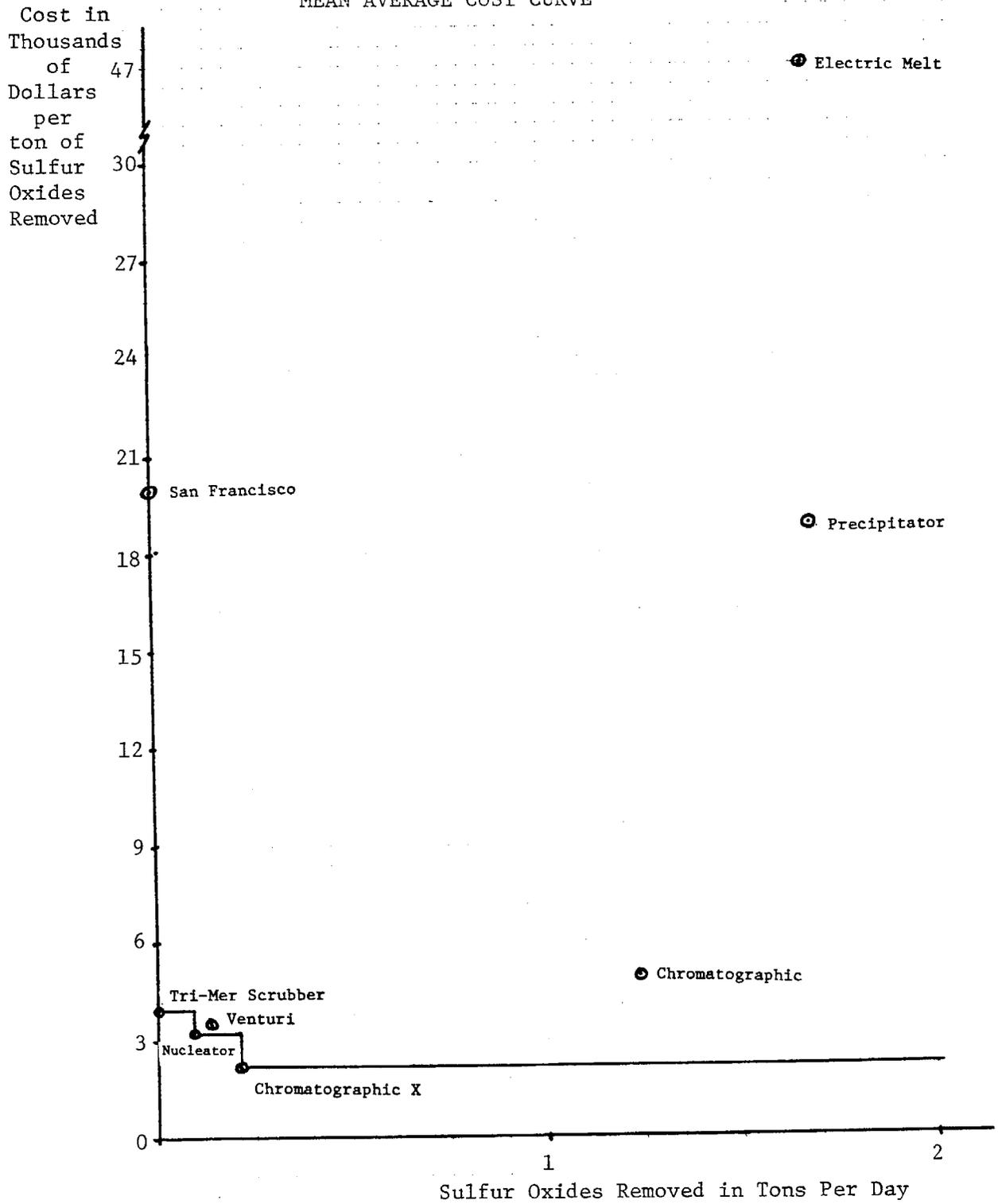
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Price per ton per day	Strategy
0-2199.00	do not abate (Z)
2199.00-19,168.08	use X for 1.79 and buy license for $.21/T SO_x$
19,168.08-46,322.67	use N for 1.91, licenses of $.09/T SO_x$
46,322.67+	use T which removes all $SO_x$

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GRAPH 1

MEAN AVERAGE COST CURVE



GRAPH 2

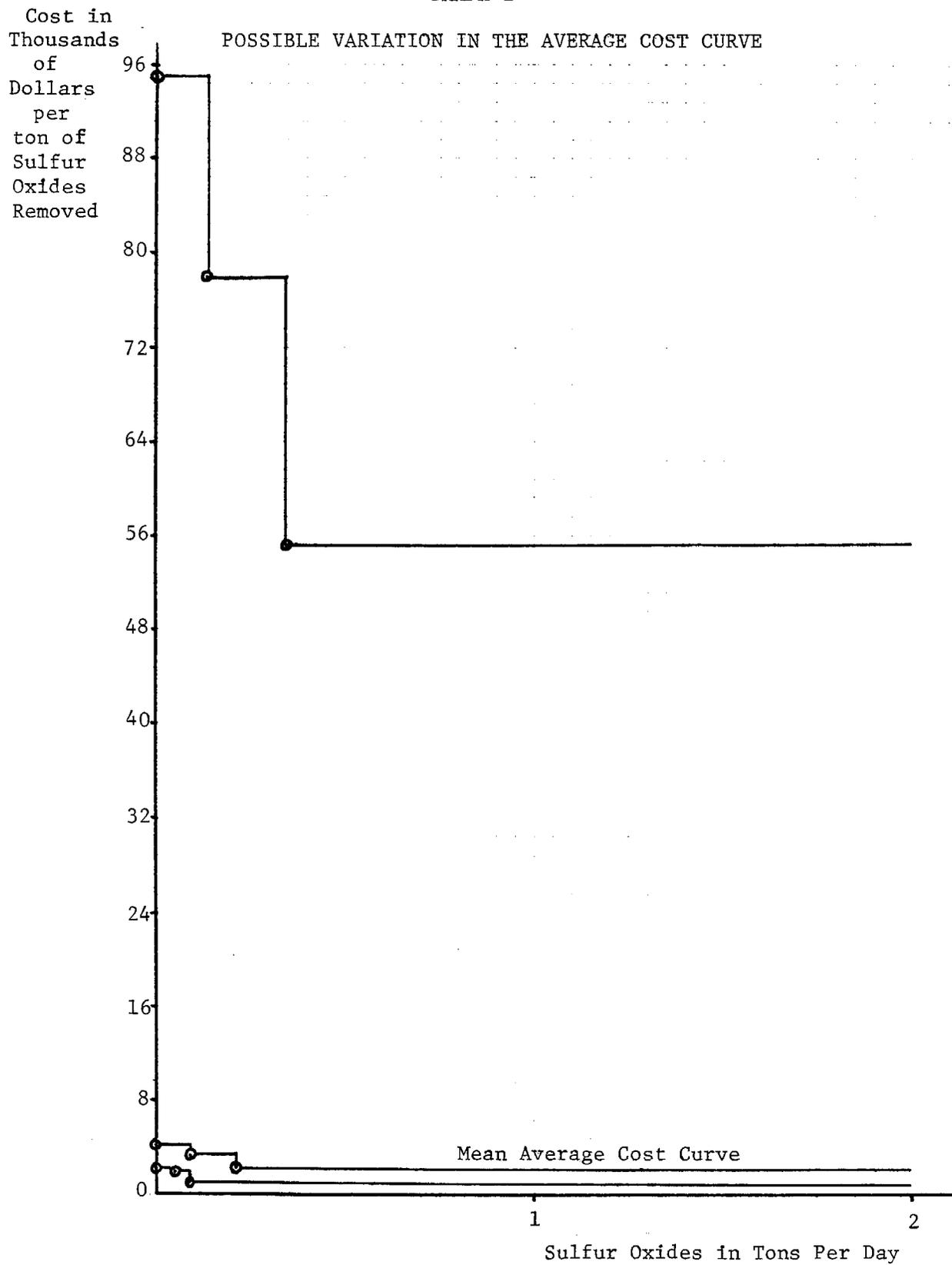
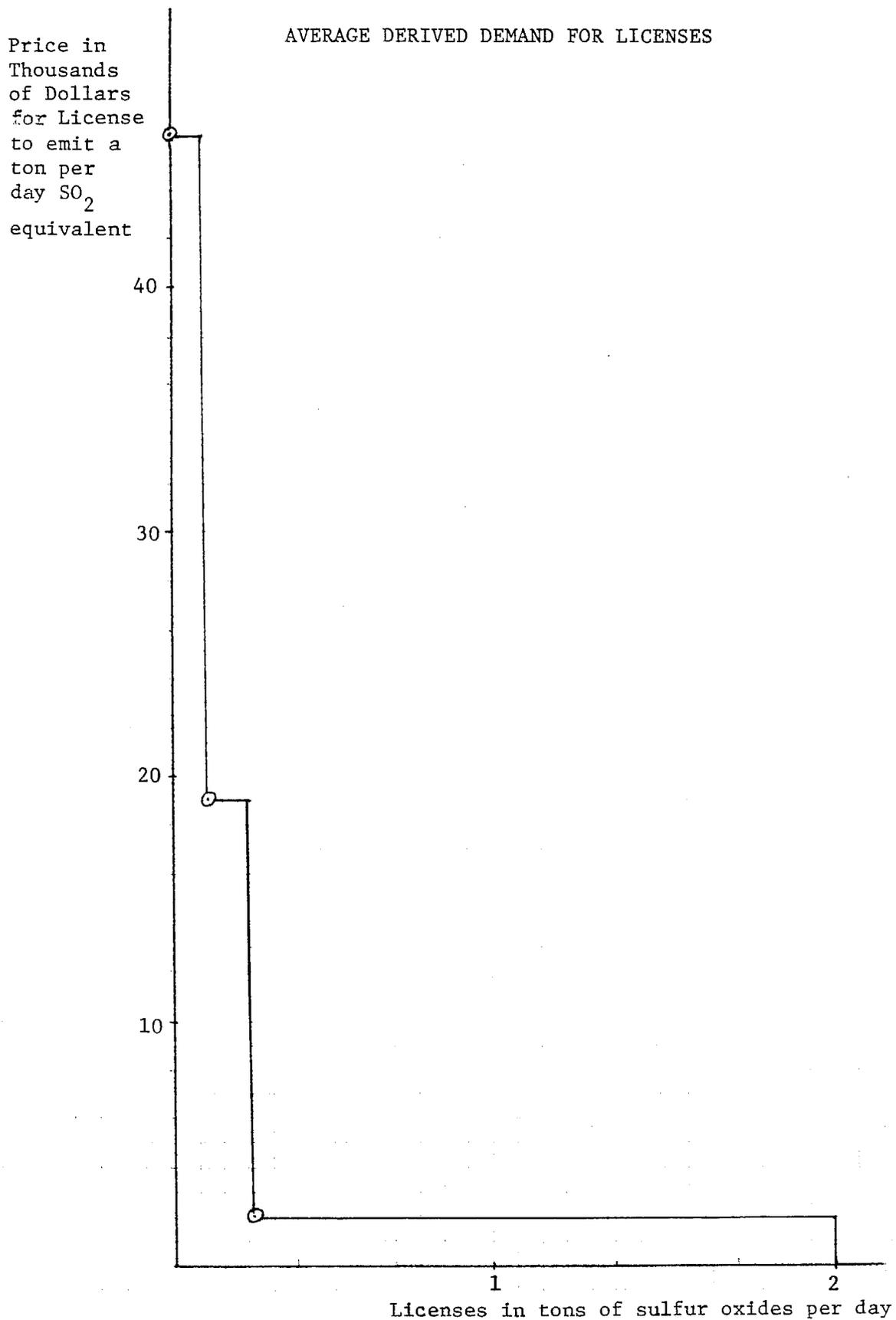


TABLE 8  
DATA FOR GRAPHS 1 AND 2

	Precip.	Chromat.	Chromat.X	Venturi	Nucleator	Elec. Melt	San Francisco	Tri-Mer Scrubber
MEAN								
Total Cost (\$)	18,833.33	4,953.49	2,199.00	3,550.24	3,265.12	>47,222.22	28,822.22	3,992.77
Net Cost (\$)	18,611.11	4,813.95	2,049.75	3,406.70	3,125.58	>47,222.22	--	--
Emissions(T)	1.68	1.24	.21	.14	.09	1.68	0	0
BEST								
Total Cost	9,826.09	2,662.50	1,099.50	1,827.59	1,712.20	>24,637.68	12,761.90	1,826.48
Net Cost	9,710.14	2,587.50	1,024.88	1,753.69	1,639.02	>24,637.68	--	--
Emissions	1.67	1.24	.09	.07	.05	1.67	0	0
WORST								
Total Cost	339,000.00	106,500.00	55,250.00	82,444.44	78,000.00	>850,000.00	536,000.00	94,977.00
Net Cost	335,000.00	103,500.00	51,500.00	79,111.11	74,666.66	>850,000.00	--	--
Emissions	1.68	1.24	.34	.22	.14	1.70	0	0

GRAPH 3

AVERAGE DERIVED DEMAND FOR LICENSES



GRAPH 4  
POSSIBLE VARIATION IN THE AVERAGE DEMAND

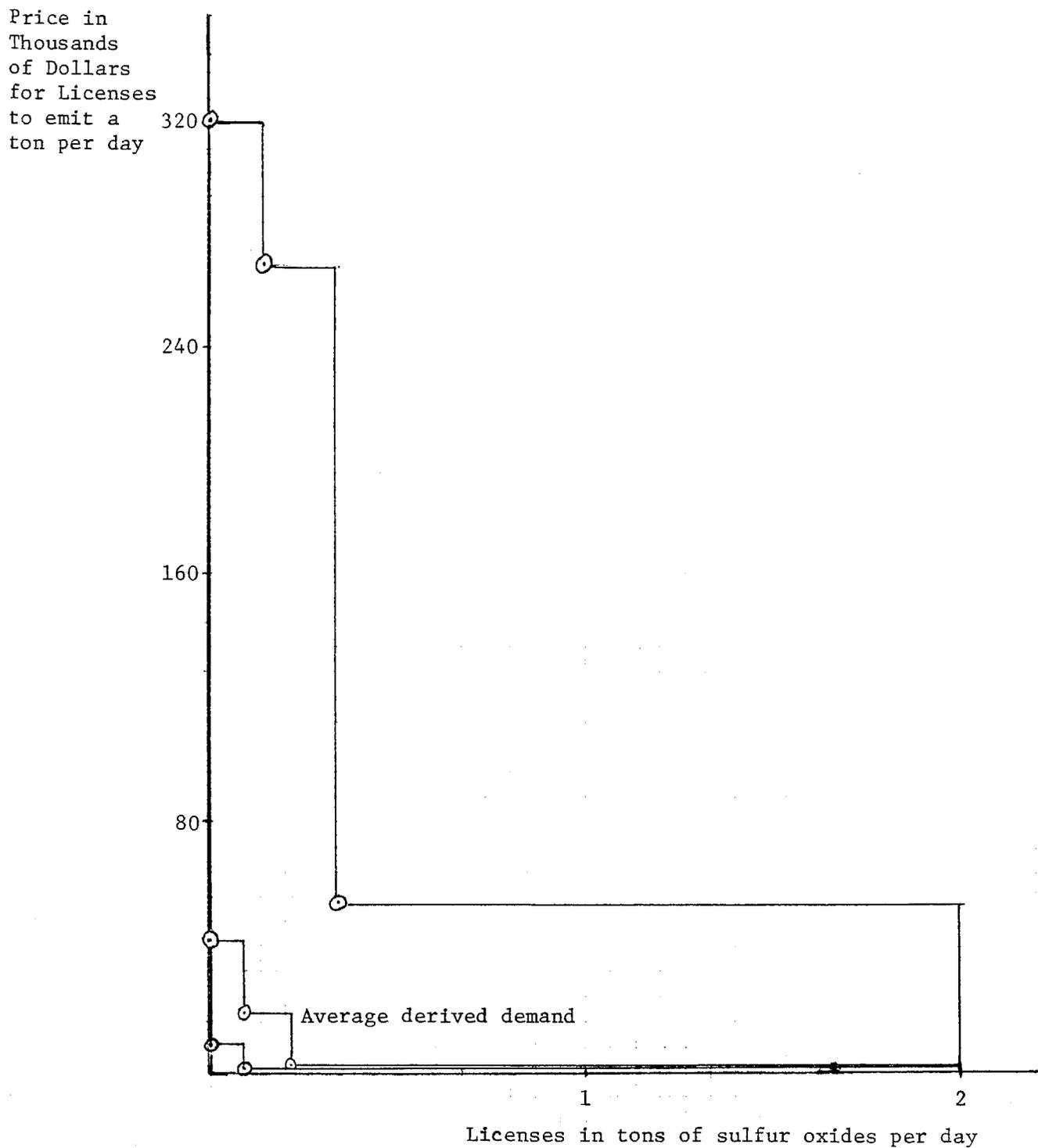


TABLE 9  
DATA FOR GRAPHS 3 AND 4

	Z	Z-X	X	X-N	N	N-T	I
AVERAGE							
C	0	3,936.21	3,936.21		6,236.38		10,405.42
A	0		1.79		1.91		2.00
$\Delta C$		3,936.21		2,300.17		4,169.04	
$\Delta A$		1.79		.12		.09	
$\Delta C/\Delta A$		2,199.00		19,168.08		46,322.67	
BEST							
C	0	1,957.52	1,957.52		3,196.09		3,652.96
A	0		1.91		1.95		2.00
$\Delta C$		1,957.52		1,238.57		456.87	
$\Delta A$		1.91		.04		.05	
$\Delta C/\Delta A$		1,024.88		30,964.25*		9,137.40	
WORST							
C	0	91,715.00	91,715.00		145,080.00		189,954.00
A	0		1.66		1.86		2.00
$\Delta C$		91,715.00		53,365.00		44,874.00	
$\Delta A$		1.66		.20		.14	
$\Delta C/\Delta A$		55,250.00		266,825.00		320,528.57	

\*This is a dominated point.

Key: C - cost, A - tons per day abated, MC - marginal cost.

## FOOTNOTES

1. Kerr produces  $200 \pm 50$  tons/day and claimed it had one-sixth of the market. Ball produces 400 tons/day and claimed only one-eighth of the market. Thus production in the basin could be anywhere between  $1,200 \pm 300$  tons and 3,200 tons per day. Glen Cass estimates that glass furnace sulfur oxides emissions for the 50 by 50 mile square grid which encompasses the major portion of the South Coast Air Basin are approximately 2 tons/day. Including off-grid emissions which are part of the South Coast Air Basin sulfur oxides modeling inventory would raise the emissions total to 2.23 tons/day.

A report prepared for the Glass Container Manufacturers Institute, "Engineering Study Program Glass Furnace Emissions Abatement," revealed that 130 tons/day glass furnaces emit 10 lbs/hr of sulfur oxides and 403 tons/day glass furnaces emit 33 lbs/hr of sulfur oxides. Based on these numbers, a 2 ton/day emissions would imply between 2,035 and 2,167 tons of glass are produced in the basin.

2. Among the glass producers and bottlers I spoke to, no one was willing to commit himself to any numbers, but Miller Brewing assured me that for "small" increases in the price of bottles, they would be able to pass on all the extra costs to the consumers, and the consumers would tend to buy about the same quantities.

3. Source is 7-Up Bottlers.
4. One interviewee claimed that the present regulation is unduly biased against mid-sized industries with a slow rate of technical change such as glass or steel. The smaller ones such as laundromats, whose weaknesses were recognized by the regulators, were exempt from the regulation. The larger ones, such as the utilities, had enough political power to manipulate the regulators to do what they wished. The mid-sized industries with rapid technological change, such as chemicals and plastics, were earning such a large profit that they could afford to comply with the regulations.
5. The problems mentioned in this and the following paragraph summarize the principal findings of a series of interviews with executives in the Los Angeles glass industry. While we are not necessarily in agreement with all of the points these people make, nonetheless these perspectives on the problems of regulation are of interest.
6. The net earnings to net sales ratios were on the average 0.0366. Thus if sales are \$35 M, net earnings are \$1.28/M. Since 400 tons are produced per day, this is \$8.77/ton.
7. Telephone interview with Rolf Jaeger, Tri-Mer Corporation, Air Pollution Control Systems, California Sales Office (714)548-5853.

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APPENDIX F-5  
PETROLEUM REFINERS

Robert W. Hahn

I. INTRODUCTION

This paper is part of a larger research effort designed to assess the viability of employing a marketable permit scheme to control sulfur oxides emissions ( $SO_x$ ) in the South Coast Air Basin. The operation of such a market proceeds in two stages. First, the overall number of permits to be issued must be decided upon. In the second stage, the marketable permits are distributed to existing firms. The permits could either be given away or auctioned. Once distributed, the firm can trade these transferable rights in much the same way anyone can buy and sell shares of stock on Wall Street.

The basic idea behind this approach to regulation is to fix some upper limit on the allowable level of emissions and then allow firms to determine, by trading, how the permits will be distributed among firms, and how much emissions each will abate. Compared with the current standards approach to regulation which proceeds on a source by source basis, the marketable permit approach is expected to lower overall expenditures of abatement for a given air quality objective. In addition, firms will be given greater flexibility in choosing control strategies.

Under this approach, a firm would not be allowed to emit sulfur oxides in excess of the number of permits which it currently held. A permit will be defined as vesting the owner with the right to emit a fixed quantity of  $SO_x$  per day (measured as  $SO_2$  equivalent). The prices for these permits would be determined in the market.

The purpose of this paper is to develop an estimate for the cost of controlling  $SO_x$  emissions from petroleum refiners that affect the sulfate air quality in the South Coast Air Basin. This information will then be used to simulate the effect of a marketable permits scheme on the decisions of the oil industry and other sources of  $SO_x$  emissions.

The oil industry poses special problems which do not arise in other industries because a refiner not only affects  $SO_x$  pollution directly through stack emissions, but also indirectly, by exerting some control over how much sulfur is distributed among the various refined products such as gasoline, jet fuel and heavy fuel oil. The first step in including the activities of petroleum refiners in a model of the market for tradable licenses is to consider the different options a refiner has with regard to sulfur acquisition and disposal. The guiding principle here is conservation of mass -- what goes into the refinery must come out somewhere. Figure 1 depicts the general choice facing the refiner. In selecting a crude input slate, the refiner chooses how much sulfur will enter the refinery. The sulfur essentially has three places it can go. It may be released to the atmosphere upon combustion of a sulfur-bearing fuel. This occurs, for example, when coke from the fluid catalytic cracker is burned and when

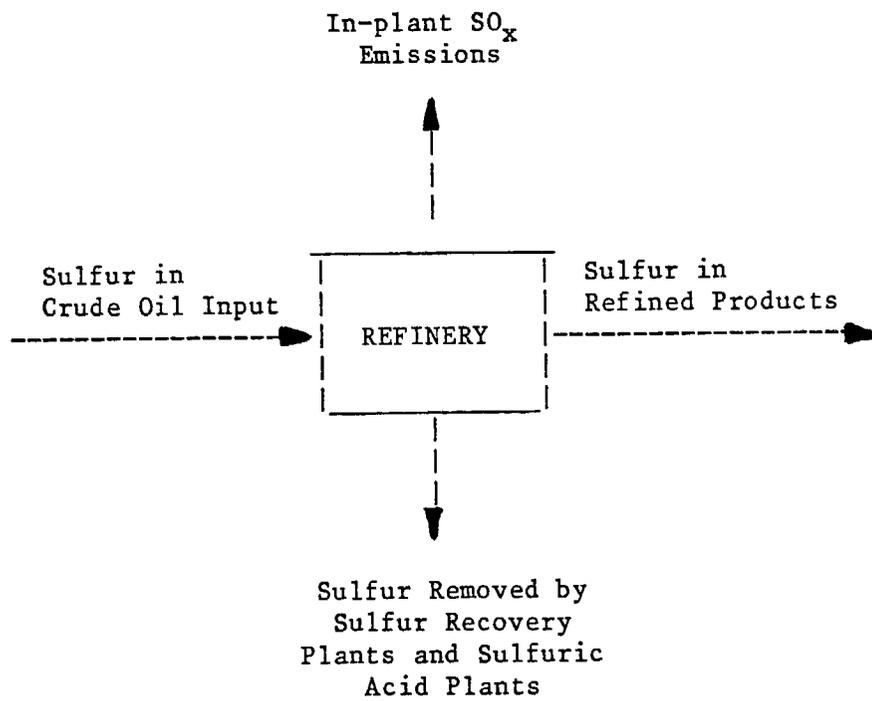


Figure 1: What to do with the sulfur?

the fuel used to run the refinery contains sulfur. A second way the sulfur may leave the refinery is by traversing a path to a plant designed to recover sulfur or a plant using  $H_2S$  gas or acid sludge in the production of sulfuric acid. If the sulfur is not emitted to the atmosphere or recovered as a by-product, it ends up in the refined products sold to industry and consumers.

This paper focuses on estimating the costs of reducing  $SO_x$  emissions by different source categories which correspond to the emissions inventory contained in Cass (1979). An alternative approach to the problem of modeling the the abatement costs of refiners is to model explicitly the sulfur and energy flows within a "typical" refiner or class of refineries. An effort is currently under way to develop such a model, but it is still in its preliminary stages.

The current effort is restricted to developing abatement costs for the following:

1. Gasoline desulfurization
2. Diesel fuel desulfurization
3.  $SO_x$  removal from Fluid Catalytic Crackers
4.  $SO_x$  removal from an Oil Field Production Process in<sup>x</sup> Orange County

Two other estimates which are needed to complete the refinery part of the model are the costs of reducing the sulfur content of residual oil and the costs of desulfurizing jet fuel. Estimates for the former are developed in Appendix F-1. As an upper bound, the cost of desulfurizing diesel fuel can be used for jet fuel if no other estimates are available.<sup>1</sup> The remainder of the paper develops estimates for the other four activities. This is followed by a brief

comparison of the estimates in light of the market simulation objective. Unless stated otherwise, all cost estimates are in 1977-1978 dollars.

## II. GASOLINE DESULFURIZATION

The data on costs for gasoline desulfurization are based on a study by Vincent (1978). Based on the assumption that the entire gasoline stock is unleaded, Vincent estimates that the average cost of moving from 500 to 400 ppm of sulfur will be \$2600/ton. A more stringent move from 500 to 300 ppm will result in an average cost of \$3100/ton.<sup>2</sup> This implies that the incremental cost of moving from 400 to 300 ppm is \$3600/ton. While the gasoline pool on which the emissions inventory is based assumes that unleaded fuel comprises 54% of the total, the figure of \$3600/ton is still applicable because the cost of removing sulfur is primarily a function of sulfur content and not the amount of lead in the gasoline. The cost estimates take account of the increased emissions that would result from the increased consumption of fuel oil.

## III. DIESEL FUEL DESULFURIZATION

Estimates for diesel fuel desulfurization depend, among other things, on the complexity of the refinery and whether equipment such as distillate hydrotreaters will need to be purchased. A study sponsored by the South Coast Air Quality Management District places the cost of reducing  $SO_x$  emissions from diesel fuel by 80% at \$250/ton.<sup>3</sup> This assumes no new equipment would be needed. A recent

report released by the California Air Resources Board estimates that costs will vary between \$1000 and \$2000 per ton of SO<sub>2</sub> reduction in a complex refinery, depending on how much equipment would be added.<sup>4</sup> We will assume that the cost of reducing sulfur oxides emissions from diesel fuel is \$1000/ton for the first 64% reduced and \$2000/ton for the next 16%.<sup>5</sup> The lower cost figure assumes that no new capital investment would be necessary for the first step, while the higher cost figure takes account of additional hydrodesulfurization, hydrogen production and sulfur recovery facilities.

#### IV. FLUID CATALYTIC CRACKERS

Data for the cost of reducing SO<sub>x</sub> emissions from fluid catalytic crackers is taken from a study by the South Coast Air Quality Management District. Decreasing emissions by 80% will cost \$810/ton. This estimate is based on the future potential of hot catalyst regeneration. An additional 10% decrease in emissions will cost \$18,700/ton.<sup>6</sup> The significant increase in cost is based on the assumption that wet scrubbers would be needed to achieve that level of abatement.

#### V. OIL FIELD PROCESSES

An oil production field in Orange County is a relatively small source of emissions, but presents an interesting example because of its location. If permits were defined in terms of emissions, this firm might be induced to put on more controls. However, if permits were defined in terms of ambient impact on, say, downtown Los Angeles,

it would probably not be cost-effective to add further controls. The basic abatement cost data have been drawn from a conversation with a company representative.<sup>7</sup> The company is considering use of a Stretford process to remove sulfur from the exhaust of the oil field enhanced recovery operation. Estimated capital costs are \$1.5 million and annual operating costs are \$60,000 (at a maximum). These figures are given in current dollars. Assuming a capital recovery factor of .2, the total annual and operating costs would be in the neighborhood of \$360,000. The process is assumed to be at least 90% efficient. According to Cass (1979), total emissions are approximately 4.3 tons/day.<sup>8</sup> Using this figure would imply the cost of reducing  $SO_x$  is approximately \$250/ton in current dollars, which corresponds to a cost of approximately \$200/ton in 1977-1978 dollars.<sup>9</sup>

## VI. THE DEMAND FOR PERMITS

The cost estimates developed in the previous section are summarized in Table 1. The corresponding derived demand for marketable permits is drawn in Figure 2. These estimates only pertain to the categories listed in the paper. The possibilities of reducing the sulfur content of jet fuel and residual fuel are not included here. The analysis indicates that the costs of controlling  $SO_x$  emissions for the petroleum industry vary by as much as two orders of magnitude, depending on the process and facility being controlled as well as the extent of control.

Table 1  
MARGINAL ABATEMENT COST DATA  
(1977 \$)

CATEGORY	BASELINE EMISSIONS <sup>a</sup> (Tons SO <sub>x</sub> /Day)	% REDUCTION	COST (\$/Ton)
Gasoline Desulfurization	28.92 <sup>b</sup>	0-25	3600
Diesel Fuel Desulfurization	70.79 <sup>c</sup>	0-64 64-80	1000 2000
Fluid Catalytic Crackers	44.95	0-80 80-90	810 18,700
Oil Field Processes	4.3	0-90	200

<sup>a</sup>Figures taken from Appendix E, Table E1.27.

<sup>b</sup>This includes emissions from all light duty vehicles.

<sup>c</sup>Source categories include Low Priority Natural Gas Customers, Heavy Highway Diesel Vehicles and Railroad Operations.

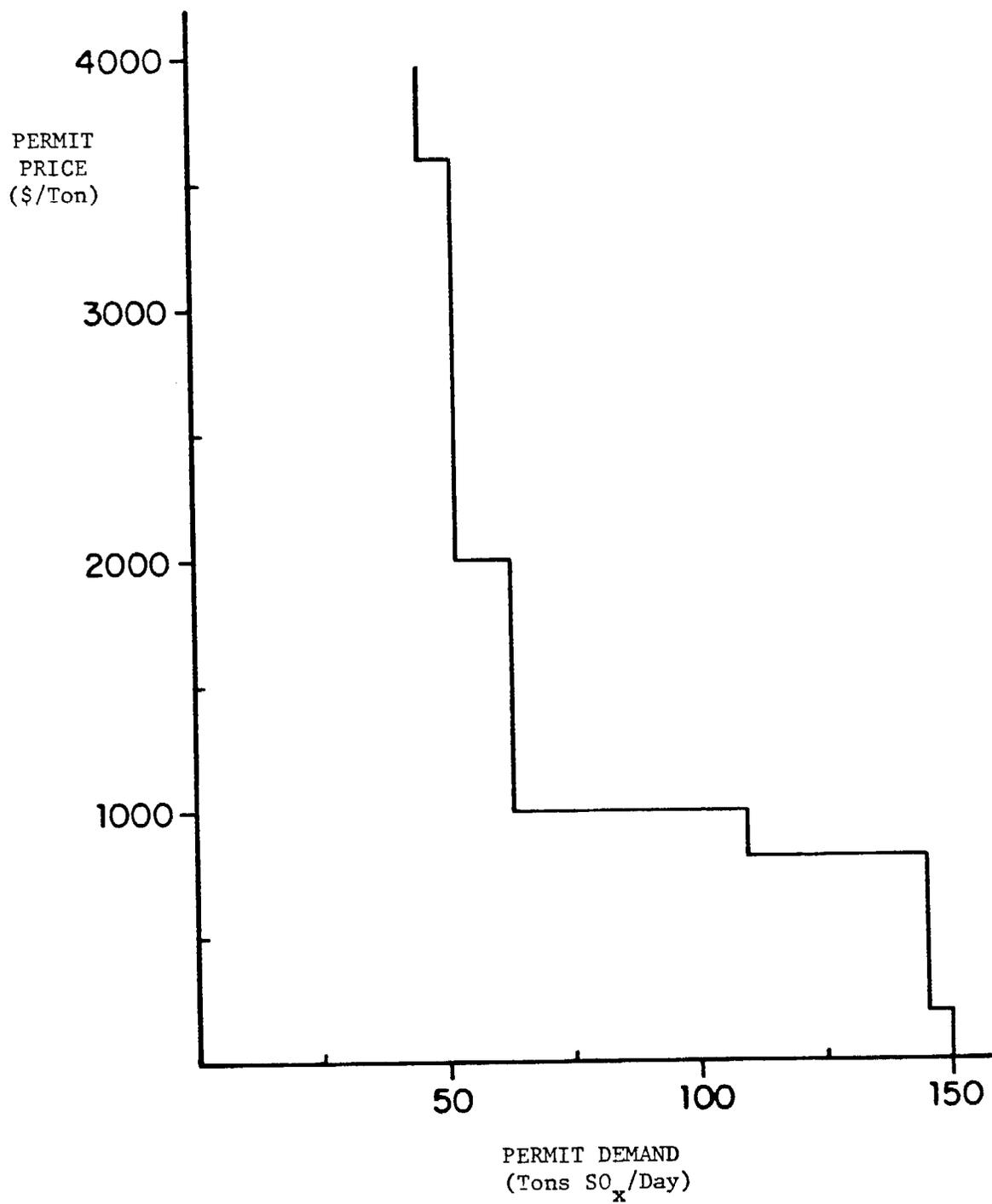


Figure 2: Estimate of Derived Demand for Permits--Refiners

## FOOTNOTES

1. Conversation with Sam York, South Coast Air Quality Management District, January 29, 1981.
2. Vincent, p. 83.
3. This estimate is taken from the Sulfur Dioxide/Sulfate Control Study: Executive Summary, p. 28. A conversation with Sam York has revealed that this number is based on the assumption that no new equipment is added. According to Mr. York, it is likely that adding such equipment would lead to an order of magnitude increase in marginal control costs.
4. "Public Hearing to Consider Amendment of Title 13 ...," p. 100. The estimate for .05% control is stated as ranging from \$.51 to \$1.01 per pound of SO<sub>2</sub> reduced for a complex refinery.
5. Our data are in terms of 1977 dollars whereas data from the California Air Resources Board are presumably given in current dollars. The reason that the figures we suggest are higher in real terms than the figures for a complex refinery is because other types of refineries have somewhat higher costs of desulfurization. The decision to add the costs of new equipment at 64% is based on a conversation with Sam York.
6. Sulfur Dioxide/Sulfate Control Study: Executive Summary, p. 28.
7. Cost estimates are based on a conversation with Alex Iwasiw on February 9, 1981.
8. Cass, Table E1.27.
9. This calculation is based on the GNP deflator data from the Survey of Current Business, p. 34.

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APPENDIX G

A THEORETICAL ANALYSIS OF THE DEMAND FOR EMISSION LICENSES

Robert W. Hahn

ABSTRACT

The issue of how firms with inputs of variable quality will react in a market for transferable emissions licenses is analyzed. First, it is shown that the derived demand for licenses will, in general, be downward sloping. This is followed by a discussion of the effects of imperfections in product and factor markets on abatement decisions.

This paper examines the qualitative effects that a market in transferable licenses in emissions will have on a firm's input decisions and its expenditure on abatement equipment. The case of the competitive firm is examined in detail, and this is compared with a firm which can exert monopoly power in product and factor markets. The model employed here differs from previous work in that the price of the variable input is explicitly related to its quality. This can be compared with the more conventional approach which treats the pollutant as a factor of production.<sup>1</sup> Several authors have shown that the derived demand for inputs of fixed price and quality are downward sloping.<sup>2</sup> In Section 1, this result is extended to the case where input quality can be varied. Section 2 compares the demand for licenses under competition with the demand for licenses when a firm can exert power over product or factor markets. In Section 3, the role of other traders and the authority issuing licenses is explicitly included in the analysis. Section 4 summarizes the results.

#### 1. The General Problem

Attention is focused on the problem of controlling emissions associated with the use of productive inputs. When the relationship between emissions and ambient pollutant concentrations is linear, then the subsequent analysis obtains for the control of secondary pollutants as well as the control of primary emissions.

The control of sulfur oxides emissions is one example for which the model would be appropriate. Sulfur enters into the production process through the use of natural resources that contain it, usually coal and petroleum used as energy inputs. When these inputs are burned some of the sulfur contained in them is converted to  $\text{SO}_2$  and  $\text{SO}_3$ . For a given abatement technology, the relationship between sulfur entering the production process and resulting emissions of sulfur oxides is approximately linear.

The firm may adopt two basic approaches to reducing emissions. It can either reduce emissions directly by purchasing equipment such as scrubbers and baghouses or it can reduce the level of pollutant entering into the production process. This latter reduction is normally accomplished by purchasing higher quality inputs, which typically cost more, by curtailing output, or by varying the amount of inputs used per unit of output in production. For simplicity, the last method for reducing emissions will be ignored. Suppose that the firm has a production function  $f(E)$ , where  $E$  represents the level of inputs. The function  $f$  is assumed to be twice differentiable and strictly concave so that  $f' > 0$  and  $f'' < 0$ .

Let  $X(R,s,E)$  characterize the firm's abatement opportunities.  $X$  is the total annual emission rate;  $R$  is the total annual expenditure on abatement; and  $s$  is the amount of the pollutant contained in a unit of the input stream,  $E$ . Emissions are assumed to decrease with greater abatement expenditures, but there are decreasing returns to

such endeavors, (i.e.,  $X_1 < 0$  and  $X_{11} > 0$ ). On the other hand, annual emissions will increase if the firm chooses lower quality inputs or increases the level of its inputs (i.e.,  $X_2 > 0$  and  $X_3 > 0$ ).

Furthermore, it will be assumed that increasing inputs will not improve the marginal effect of a given pollutant content, and may make it worse (i.e.,  $X_{23} \geq 0$ ).<sup>3</sup> The firm's problem is to maximize profits, or the difference between total revenues and the sum of input costs, abatement costs and license costs. Formally, we have:

$$\begin{aligned} & \text{Maximize } pf(E) - e(s)E - wX(R, s, E) - R \\ & \quad R, s, E \end{aligned} \quad (1)$$

where

$p$  = price of output,

$e(s)$  = unit price of inputs;  $e' < 0$   $e'' > 0$ , and

$w$  = license price.

The price of inputs is presumed to be a convex function of the pollutant content. From this, it immediately follows that a firm would never wish to use two or more different quality inputs simultaneously, where such inputs are defined solely in terms of pollutant content.<sup>4</sup> Empirically, this relationship has been shown to hold approximately for heavy fuel oil prices in Los Angeles.<sup>5</sup>

First-order conditions for an interior solution are given by:

$$-wX_1 - 1 = 0 \quad (2)$$

$$-e'E - wX_2 = 0 \quad (3)$$

$$pf' - e - wX_3 = 0 \quad (4)$$

Equation (2) says that at the margin, an additional dollar spent on abatement equipment will be exactly offset by the savings resulting from decreased emissions. Equation (3) balances the reduction in emissions from buying higher quality inputs against the increase in the cost of buying licenses. Equation (4) equates the marginal revenue product of using an additional unit of inputs with the increase in the cost of input, which consists of two components: the direct cost of inputs,  $e$ , and the indirect cost due to having to purchase more licenses,  $wX_3$ .

The interesting comparative statics questions revolve around the effect of a change in the license price on abatement expenditures, the pollutant content of inputs, the level of inputs, and hence, the ultimate level of emissions which is chosen. Totally differentiating the first order conditions gives rise to the following Hessian matrix,  $C$ :

$$C = \begin{bmatrix} -wX_{11} & -wX_{12} & -wX_{13} \\ -wX_{12} & (-e''E - wX_{22}) & (-e' - wX_{23}) \\ -wX_{13} & (-e' - wX_{23}) & (pf'' - wX_{33}) \end{bmatrix}$$

Let  $C_{ij}$  denote the  $ij$ th cofactor of  $C$  and  $[C]$  denote the determinant. Performing the comparative statics yields expressions for the effect of a change in license price on the endogenous variables:

$$\frac{\partial R}{\partial w} = \frac{1}{[C]} [C_{11}X_1 + C_{12}X_2 + C_{13}X_3] \quad (5)$$

$$\frac{\partial s}{\partial w} = \frac{1}{[C]} [C_{12}X_1 + C_{22}X_2 + C_{23}X_3] \quad (6)$$

$$\frac{\partial E}{\partial w} = \frac{1}{[C]} [C_{13}X_1 + C_{23}X_2 + C_{33}X_3] \quad (7)$$

$$\frac{\partial X}{\partial w} = X_1 \frac{\partial R}{\partial w} + X_2 \frac{\partial s}{\partial w} + X_3 \frac{\partial E}{\partial w} \quad (8)$$

Assume that sufficiency conditions for an interior maximum are met.<sup>6</sup>

This implies that  $C$  is negative definite. Even with this assumption,  $\frac{\partial R}{\partial w}$ ,  $\frac{\partial s}{\partial w}$  and  $\frac{\partial E}{\partial w}$  cannot be signed unambiguously. However, it is possible to show that the demand for licenses is downward sloping (i.e.,  $\frac{\partial X}{\partial w} < 0$ ). Substituting equations (5) - (7) into (8) yields:

$$\frac{\partial X}{\partial w} = \frac{1}{|C|} \begin{bmatrix} (X_1, X_2, X_3) & \begin{bmatrix} C_{11} & C_{21} & C_{31} \\ C_{12} & C_{22} & C_{32} \\ C_{13} & C_{23} & C_{33} \end{bmatrix} & \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \end{bmatrix} \quad (9)$$

Because  $C$  is negative definite, this implies  $C^{-1}$  is negative definite.

Thus, equation (9) indicates that  $\frac{\partial X}{\partial w} < 0$ .

While the sign of the terms in equations (5) - (7) cannot be determined exactly, it is possible to infer from equation (9) that an

increase in the price of a license will induce at least one of the following events: (1) an increase in the level of annual abatement expenditures, (2) a decrease in the pollutant content of inputs or (3) a decrease in the level of inputs. Of course, it is possible that more than one of these events will occur in response to a license price increase, but at least one such event must occur.

The result derived here concerning the downward sloping demand curves also holds for the case in which the level of inputs are fixed, but the quality is allowed to vary. This latter case may be applicable to several firms in the short run. A case in point would be electric utilities who burn high sulfur residual fuel oils. The only difference between the case when inputs are constrained and the more general case is that in the constrained case, an increase in the license price will lead to an increase in abatement expenditures or a decrease in the pollutant content of inputs, and possibly both.

It is a straightforward matter to show a monopolist will have a downward sloping derived demand for licenses in this general case. However, at this level of analysis, it is not obvious how the demand by a competitive firm compares with the demand by a firm that can exert market power. To allow for a case by case comparison, it is helpful to consider a less general formulation. This is the subject of the next section.

## 2. A Comparison of Competition with Market Power

A simple case to analyze is where the pollutant in the inputs just equals emissions; that is, no abatement can be achieved through expenditure on equipment. In this case, reductions can be achieved by reducing the pollutant content of inputs and/or reducing the level of inputs. One example would be the containment of sulfur oxides through the purchase of lower sulfur fuels. Formally, the firm's problem may be written as follows:

$$\begin{array}{l} \text{Maximize } pf(E) - e(s)E - wsE \\ s, E \end{array} \quad (10)$$

First-order conditions for an interior maximum are given by:

$$-e'E - wE = 0 \quad (11)$$

$$pf' - e - ws = 0. \quad (12)$$

Equation (11) indicates that  $s$  should be chosen so as to equate the cost of polluting more,  $w$ , with the marginal cost of buying higher quality inputs,  $-e'(s)$ . Equation (12) balances the marginal revenue product with an increase in input costs.

Define  $B$  to be the Hessian associated with (10). Then,

$$B = \begin{bmatrix} -e''(s)E & 0 \\ 0 & pf'' \end{bmatrix} \quad (13)$$

From the assumptions on  $e$  and  $f$ ,  $B$  is negative definite. An

examination of the effects of a change in the price of a license on pollutant content and the overall level of inputs yields:

$$\frac{\partial s}{\partial w} = \frac{1}{e''(s)} < 0 \quad (14)$$

$$\frac{\partial E}{\partial w} = \frac{s}{pf''} < 0 \quad (15)$$

Equation (14) says that the pollutant content decreases with an increase in the price of a license while (15) says that the level of inputs also declines. Since the overall level of emissions is given by  $sE$ , it is readily seen that emissions decrease in response to an increase in the price of a license.

It is possible to compare the situation when the firm can exert market power with the competitive case by making suitable changes in (10) and carrying out the required optimization. Three cases will be considered: first, the case of pure monopoly; next, the case when a firm exerts some influence over the energy market and finally, the case when a firm can dominate the license market. The monopolist's problem is the same as above, except now  $p = p(f(E))$ , which gives:

$$\text{Maximize } p(f(E))f(E) - e(s)E - wsE \quad (16)$$

$s, E$

First-order conditions for an interior maximum are given by:

$$-e'(s)E - wE = 0 \quad (17)$$

$$pf' + fp'f' - e(s) - ws = 0 \quad (18)$$

Equation (17) is identical with equation (11). From the assumptions on  $e$ , the value for  $s$  which solves (17) (assuming one exists) will be unique.<sup>7</sup> Thus, the monopolist and perfect competitor will choose the same pollutant content. To determine who would pollute more, it is only necessary to consider whether the monopolist will use more or fewer inputs than in the competitive case. Assuming the revenue function for the monopolist is strictly concave and an interior solution to the problem exists, then the monopolist will use less energy and, hence, pollute less than his competitive counterpart. To see this, define the revenue function:  $R(E) = p(f(E))f(E)$ . The usual differentiability assumptions imply  $R' > 0$  and  $R'' < 0$ . Comparing conditions (12) and (18), it is clear that setting  $E$  at the optimal level in the competitive case will yield the following inequality:

$$pf' + fp'f' < e(s) + ws, \quad (19)$$

since  $fp'f' < 0$ . The question is whether (19) can be brought into equality by adjusting  $E$ . From (11) and (17), we saw that the pollutant content is identical for the two cases, independent of the level of inputs which is chosen. This means that the expression on the right-hand side of (19) can be treated as a constant. Noting that the left-hand side of (19) equals  $R'(E)$ , it immediately follows that the only way to bring (19) back into equality is to decrease  $E$  from the competitive level.

So far, we have derived conditions under which the monopolist will emit less and produce less than in the perfectly competitive case. The key assumption concerned the shape of the revenue function. This assumption is also critical for deriving the comparative statics results given below:

$$\frac{\partial s}{\partial w} = -\frac{1}{e''(s)} < 0 \quad (20)$$

$$\frac{\partial E}{\partial w} = \frac{s}{R''(E)} < 0 \quad (21)$$

A comparison of Equations (14) and (20) reveals that the effect of a change in license price on pollutant content will be the same for the monopolist and the competitive firm for a given level of input quality. The effect of a change in license price on input usage will, in general, differ, even for inputs of the same quality. However, the analysis reveals that the qualitative results under monopoly and competition are the same. Both pollutant content and input usage decline with an increase in the price of a license.

The results for the case in which the firm faces an upward sloping supply curve for inputs closely parallel the monopoly case. The problem is the same as the competitive case except  $e$  is now a function of  $s$  and  $E$ . The firm tries to:

$$\begin{aligned} &\text{Maximize } pf(E) - e(s,E)E - wsE. && (22) \\ &\quad s, E \end{aligned}$$

The price of inputs is assumed to increase as demand increases

( $e_2 > 0$ ). In addition, it will be assumed that changing the pollutant content will have no influence on the relationship between input demand and price ( $e_{12} = 0$ ). This latter assumption essentially allows the solution to the first-order conditions to proceed in two stages. First, the pollutant content is determined, and then the level of inputs is chosen.

First order conditions for an interior maximum to (22) are given by:

$$- e_1 E - wE = 0 \quad (23)$$

$$pf' - e - Ee_2 - ws = 0 \quad (24)$$

Equation (23) determines the optimal pollutant content,  $s$ . If  $E$  is set to the optimal competitive level, this gives rise to the following inequality:

$$pf' - Ee_2 < e + ws \quad (25)$$

The problem is to adjust  $E$  so as to bring (24) into equality so that the first order conditions are satisfied. Assuming that the costs of inputs  $eE$ , is a convex function in  $E$  (for any given  $s$ ) is sufficient to insure that the optimal level of inputs will be less than the competitive case.

The problem of assessing the behavior of a firm which can exert control over the market price for emissions licenses is similar to the previous case, but somewhat more complex. The general problem

is the same as in the competitive case except now license price is presumed to be negatively related to emissions so that  $w=w(sE)$  and  $w' > 0$ . The conventional approach to such problems is to disregard output effects and solve the following cost minimization.

$$\underset{s}{\text{Minimize}} C(s) = e(s)\bar{E} + w(s\bar{E})s\bar{E}, \quad (26)$$

where the level of inputs is fixed at  $\bar{E}$ . There are two basic reasons for ignoring output effects: first, because the comparative statics results are ambiguous when these effects are included, and secondly, because output effects may not be very important in the short-run.

Dividing (26) by  $\bar{E}$  and solving the equivalent minimization problem yields the following first order condition:

$$e'(s) + w + s\bar{E}w' = 0 \quad (27)$$

Equation (27) balances the marginal cost of buying more licenses,  $w + s\bar{E}w'$ , with the cost of buying lower sulfur fuel. If the cost function,  $C(s)$ , is convex so that  $C''(s) \geq 0$ , then the optimal pollutant content chosen will be less than in the competitive case, provided the output produced is the same. The argument parallels the case of monopoly and will not be repeated here. Instead, we turn to an alternative formulation of the market power problem which explicitly considers the role of other agents.

### 3. Market Power: A More General Approach

The subsequent analysis considers the case where one agent exercises market power, while all other agents assume they cannot affect the price of a license or the quantity of licenses issued,  $L$ , (i.e., a Stackelberg "leader and follower" model). The aggregate reported demand curve for all agents excluding  $i$  is denoted by  $Q^{-i}(w)$ ; it is assumed that  $Q^{-i}$  is twice continuously differentiable and downward sloping, i.e.,  $Q^{-i'} < 0$ . Let  $Q(w)$  represent the aggregation of  $i$ 's true demand for licenses,  $Q_i(w)$ , with  $Q^{-i}(w)$ , which  $i$  takes as given. The quantity of licenses supplied by the "center" is given by  $C(w)$  which is presumed to be twice continuously differentiable and strictly increasing, i.e.,  $C' > 0$ . The curves are illustrated in Figure 1.

Agent  $i$  is aware that he may choose any point on the center's supply curve above the price of  $w_0$ , which represents the equilibrium price if  $i$  submits no demand. A price of  $w_1$ , assumed to be greater than  $w_0$ , would result if  $i$  submitted his true demand.

To derive  $i$ 's best approach to the problem, first note that his effective supply, denoted as  $S(w)$  is given by:

$$S(w) = C(w) - Q^{-i}(w) \quad \text{for } w \geq w_0 \quad (28)$$

Because  $C' > 0$  and  $Q^{-i'} < 0$ ,  $S'(w) > 0$ , which means that agent  $i$ 's effective supply curve of licenses to  $i$  is strictly increasing.

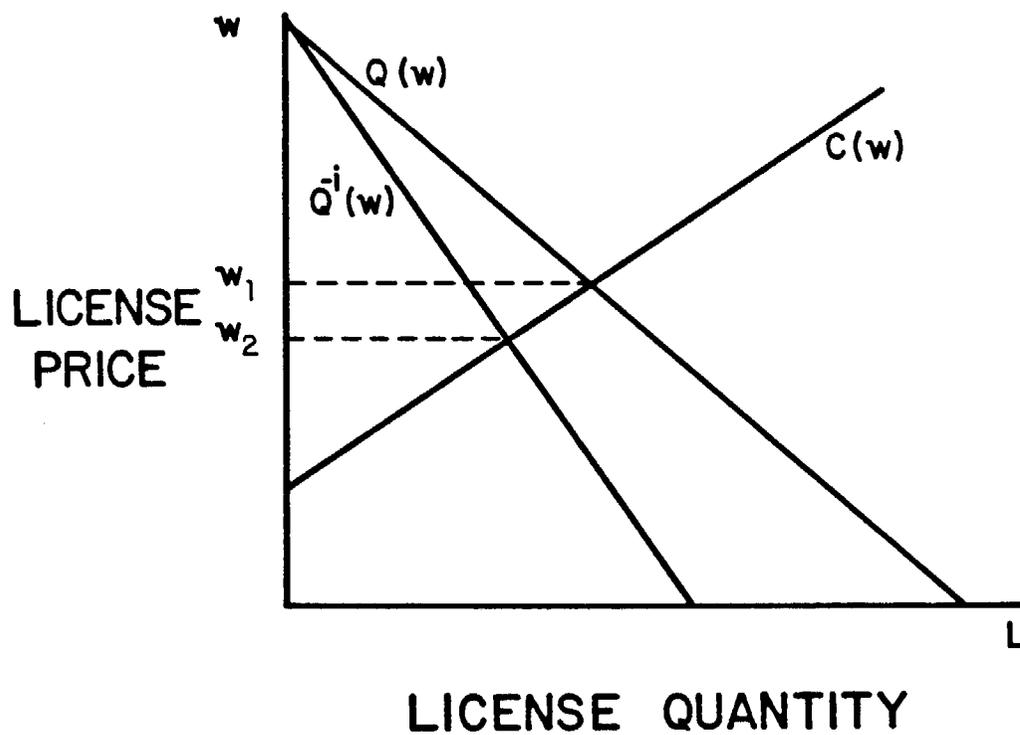


FIGURE 1

The General Supply and Demand Problem

Define the inverse of  $S(w)$  as  $s(L)$ . Since  $S$  is upward sloping, so is its inverse, i.e.,

$$w = s(L) \quad s' > 0 \quad (29)$$

Finally, define agent  $i$ 's inverse demand function as  $d_i(L)$ ; this function is presumed to be strictly decreasing, i.e.,  $d_i' < 0$ . Agent  $i$ 's problem is depicted in Figure 2.  $L_1$  represents the quantity of licenses agent  $i$  receives if he reveals his true demand and the market clears at  $w_1$ .

The question which  $i$  must address is whether it is in his interest to misstate his true demand, and if so, in which direction. To answer this question  $i$ 's interest is defined as follows:

$$\text{Agent } i\text{'s net gain} = \int_0^L d_i(q) dq - s(L)L \quad (30)$$

Equation (30) says that the gain  $i$  derives by purchasing  $L$  licenses is given by the difference between the area under his inverse demand curve between 0 and  $L$  and the costs of purchasing  $L$  licenses. With this measure of welfare, it is apparent that agent  $i$  will never demand more than  $L_1$  licenses since he not only has to pay more for all inframarginal units, but he also loses on the marginal units as well. The only other possibility is that agent  $i$  demands fewer than  $L_1$  licenses. Suppose that he chooses a level of licenses equal to  $L_2$  as illustrated in Figure 2. To compare this outcome to the situation in which  $i$  receives  $L_1$  licenses, it is convenient to sort out his gains

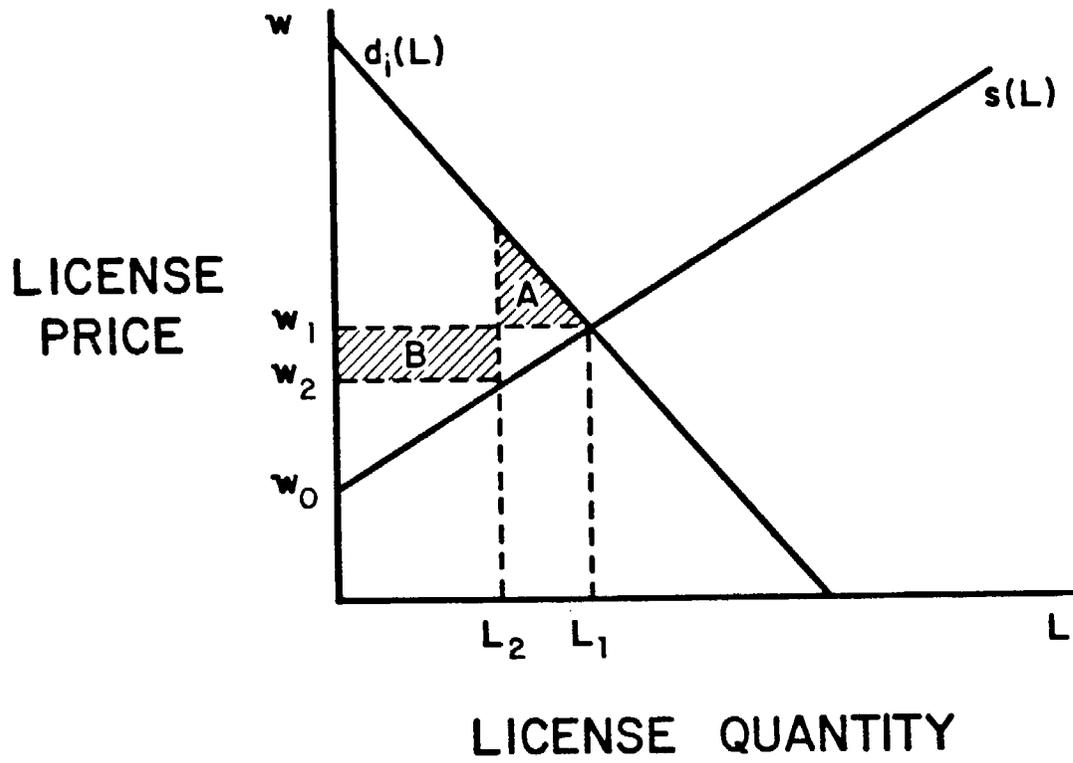


FIGURE 2

Agent  $i$ 's Problem

and losses in a systematic manner. The gains to  $i$  which result from being charged a price  $w_2$  instead of  $w_1$  are noted by the shaded area B. His losses due to the fact he purchases  $(L_1 - L_2)$  fewer licenses are represented by area A. If  $(B - A)$  is positive, then we may conclude that  $i$ 's welfare associated with  $(L_2, w_2)$  exceeds that associated with revealing his truthful demand,  $(L_1, w_1)$ . The problem of showing that it is always in  $i$ 's interest to overabate is equivalent to showing that there exists an  $L \in (0, L_1)$  for which  $(B - A)$  is positive.

Maximizing (30) with respect to  $L$  and assuming an interior maximum exists yields the following first order condition:

$$d_i(L)(s(L) + Ls'(L)) = 0 \quad (31)$$

Noting  $s'(L) > 0$  implies:

$$d_i(L_1) < s(L_1) + L_1 s'(L_1) \quad (32)$$

To bring (32) back into equality requires that the  $L$  selected be less than  $L_1$ . This shows that it is in agent  $i$ 's interest to underrepresent his demand for pollution emission provided that there is no subsequent trading of licenses, agent  $i$  knows the demand curve of all other agents and the supply curve of the center, and the second order conditions are satisfied. It is of some importance to know what conditions on the demand or supply curve would guarantee that the stationary point is a local maximum. The second order sufficiency conditions require:

$$d'_i(L) - 2s'(L) - Ls''(L) < 0 \quad (33)$$

From (33), we see that it is sufficient to presume that the rate of change of the slope of the effective supply curve,  $s''(L)$ , is nonnegative.<sup>8</sup>

The problem analyzed above parallels the case of pure monoposony very closely. The only difference is that agent  $i$  is not the only buyer, and hence, must consider how the demand of others will affect his supply. The qualitative results which emerge in the two problems are the same, namely that output and price are both below the level they would have reached in the presence of competition.

The extreme cases were not considered in the analysis. If agent  $i$ 's effective supply curve does not vary with price, then he will demand  $L_1$  licenses since, by assumption, he cannot exert any downward pressure on the price of a license. In this case  $i$  would perceive the license market in the same light as an emissions tax. Another case not considered is when the center fixes the supply of licenses so that  $C'(w) = 0$ . In this case, the result still obtains that the firms with market power will overabate.

The principal result is called into question, however, when any "real world" considerations are brought to bear on the problem. For example, an incomplete knowledge of others' demand curves and the center's supply curve would mean that agent  $i$  would have to guess at the equilibrium price in his absence. Of course, knowing the

equilibrium price is not enough. Agent  $i$  cannot construct his effective supply curve without knowing the center's supply and others' demands over a fairly wide range. The addition of secondary markets further complicates the issue. The clearing price expected in the secondary markets is likely to vary across agents and will affect each individual's behavior in the initial auction. Without explicit modeling of such problems, it is a little premature to conclude that market power will result in overabatement.

#### 4. Conclusions

The analysis focused on the derived demand for tradable licenses. In the general case it was found that introducing inputs of different quality did not change the basic result that the derived demand was downward sloping. This holds both for the monopolist and the competitive firm. A comparison of three cases of market power in a more restricted setting revealed that in all three cases, firms would tend to overabate in comparison to the competitive firm. A more general analysis of the case when a firm can dominate the license market indicated that the assumptions required to obtain the overabatement result may be too restrictive. This is one area which merits further thought if marketable permits are to become a reality.

## Footnotes

1. For example, see Baumol and Oates (1975), p. 35ff.
2. For examples, see Samuelson (1974), pp. 76-78, Russell (1964) and Winch (1965).
3. This assumption can be explained in terms of the desulfurization of fuel oil. Suppose the effect of desulfurization is to remove a constant fraction  $(1 - \frac{1}{n})$  of total potential emissions,  $sE$ . Total expenditure on abatement is constant by assumption. The problem is to consider how  $\frac{\partial X}{\partial s}$  changes as inputs increase. Consider a discrete change in inputs from  $E$  to  $(E + \Delta E)$ . Before the change,  $\frac{\Delta X}{\Delta s} = \frac{1}{n}\Delta s E$ . After the change  $\frac{\Delta X}{\Delta s} = \frac{1}{n}\Delta s (E + \Delta E)$ . In the limit, it is apparent that  $X_{23} \geq 0$ .
4. The proof is straightforward. Suppose the firm wishes to use two different inputs with respective costs  $e(s_1)$  and  $e(s_2)$ . Let  $\lambda$  equal the fraction spent on the first type and  $(1-\lambda)$  be the fraction spent on the second. Then, the average cost of inputs would be  $[\lambda e(s_1) + (1-\lambda)e(s_2)] > e(\lambda s + (1-\lambda)s_2)$ . Thus, using inputs of the same quality with the equivalent pollutant content would be cheaper. If the firm wishes to purchase  $n$  different quality inputs, where  $n$  is arbitrary, the same line of reasoning holds.

The proof assumes, of course, that any convex combination of pollutant contents are available for values of  $\lambda$  on the unit interval. In the case of sulfur in fuel oil, this is a reasonable approximation.

5. On this point, see Chapter 3 of "Implementing Tradable Emission Licenses: Sulfur Oxides in the Los Angeles Air Shed," written by William Rogerson.

6. For the problem to make sense,  $R$ ,  $s$ , and  $E$  must be nonnegative. These constraints are assumed to be ineffective.

7. For example, if  $\lim_{s \rightarrow 0} e'(s) = +\infty$  and  $\lim_{s \rightarrow +\infty} e'(s) = 0$  (i.e.,  $e$  is a "neoclassical" function), then for any  $w > 0$ , (17) has a unique positive solution in  $s$ .

8. In the economics literature the abatement cost function for all firms is typically presumed to be twice differentiable and strictly convex. Accepting this assumption would mean that a sufficient condition for a global maximum on  $(0, L_1)$  would be that  $C''(w) \geq 0$ . For a specific example, see Ackerman, p. 279.

## References

- Ackerman, B.A., et al. (1974), The Uncertain Search for Environmental Quality, The Free Press, New York.
- Baumol, W.J. and Oates, W.E. (1975), The Theory of Environmental Policy, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.
- Cass, G.R. et al. (1980), "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed," prepared for the National Commission on Air Quality, Washington, D.C.
- Russell, R.R. (1964), "A Graphical Proof of the Impossibility of a Positively Inclined Demand Curve for a Factor of Production," American Economic Review, 54, 726-732.
- Samuelson, P.A. (1974), Foundations of Economic Analysis, Atheneum, New York.
- Winch, D.M. (1965), "The Demand Curve for a Factor of Production: Comment," American Economic Review, 55, 856-861.

APPENDIX H  
DATA FOR MARKETABLE PERMITS STUDY

Robert W. Hahn

I. Introduction

This paper discusses the data which are used to derive the calculations on which the market simulations are based for the marketable permits study. Calculations based on these data are presented in Hahn (1981a), Chapter 4.

There are three sets of data representing the derived demand for marketable permits, and three sets of air quality data that are used in Hahn (1981a). The three sets of demand data correspond to three different natural gas supply scenarios: low, high and historical. The three sets of air quality data link sulfur oxides emissions in the South Coast Air Basin of California to sulfate air quality. All of the air quality data presented here are associated with the case of low natural gas supply. The three different sets of air quality data correspond to different assumptions about meteorological conditions. Year 1 corresponds to meteorological conditions in 1972; Year 2 corresponds to meteorological conditions in 1973; and Year 3 corresponds to meteorological conditions in 1974.

The demand curve links the willingness to pay for permits to quantity demanded. It should be understood that the cost data is preliminary and should not be used without the permission of the author. Units for the demand estimates are tons/day of sulfur dioxide

(SO<sub>2</sub>) equivalent and dollars/ton. All estimates are given in 1977-1978 dollars.

The air quality data link sulfur oxides (SO<sub>x</sub>) emissions from a particular source class to air quality at a given monitoring site. Air quality is measured in terms of the amount of sulfate (SO<sub>4</sub><sup>2-</sup>) per unit volume. Data converting emissions to air quality are given in  $\mu\text{gm}/\text{m}^3/\text{ton}$  per day.

## II. Abatement Cost Data for Low Natural Gas Supply

Demand is based on projected emissions in the early 1980's under the assumption 1977 regulations concerning SO<sub>x</sub> emissions are effective. There are 45 activities for the low natural gas supply case. They are described in Table 1. Table 2 gives the relevant cost data for each of the activities in Table 1. Data on SO<sub>x</sub> emissions for Table 2 are taken from Cass (1979). With each activity there are three associated numbers written in double precision intended for use in a FORTRAN program --hence, the "D+0" notation. The first column of numbers corresponds to the willingness to pay for reducing one ton SO<sub>2</sub> equivalent per day. If there is a negative number in this column, then the activity has no known controls. The second column of numbers corresponds to the number of tons/day that are associated with the marginal cost of abatement given in Column 1. The final column corresponds to any uncontrolled emissions for the activity in question. After each set of activities, supporting materials are noted.

### III. Abatement Cost Data for High Natural Gas Supply

There are 39 activities for the high natural gas supply case. They are described in Table 3. Table 4 gives the relevant cost data for each of the activities in Table 3. Data on  $\text{SO}_x$  emissions for Table 4 are based on Cass (1979). Appropriate adjustments are made in emissions to reflect the higher supply of natural gas. See Hahn (1981b) for a more detailed discussion. The interpretation of the columns in Table 4 is the same as in Table 2. After each set of activities, supporting materials are noted.

### IV. Abatement Cost Data for Historical Natural Gas Supply

There are 48 activities for the historical natural gas supply case. They are described in Table 5. Table 6 gives the relevant cost data for each of the activities in Table 5. Data on  $\text{SO}_x$  emissions for Table 5 are based on Cass (1978). See Hahn (1981b) for a more detailed discussion. The interpretation of the columns in Table 6 is the same as in Table 2. After each set of activities, supporting materials are noted.

### V. The Relationship between Emissions and Air and Air Quality

This section summarizes the set of linear transfer coefficients which are used to relate source emissions to annual average air quality. Recall from Table 1 that there are 45 activities for the low natural gas case. Coefficients will be needed which link the seventeen

monitoring sites listed in Table 7 to these 45 activities.

Table 8 links the 17 receptor sites to 20 generic activity classes for each of the three years which are used in the analysis. For a more detailed discussion of the meaning of these activity classes, the reader is referred to Cass (1979). The unit of the source receptor coefficient is  $\mu\text{gm}/\text{m}^3/\text{ton}$  per day. For example, if the coefficient for a given source-receptor relationship were .02, this would imply that a daily emissions rate of 2 tons of  $\text{SO}_x$  would result in  $.04 \mu\text{gm}/\text{m}^3$  of sulfate.

The next step in the analysis is to link the generic activity classes to the activities given in Table 1. This is done in Table 9. At this point, the change in sulfate air quality at the various monitoring sites can be predicted given any change in the distribution of emissions from the 45 source categories listed in Table 1. To predict the absolute level of sulfate air quality, background levels must be added to the change in air quality resulting from anthropogenic sources. These figures, taken from Cass (1978, p.288), are reproduced in Table 10.

## VI. Concluding Remarks

This presentation of the data is designed to be concise. Anyone interested in using this data set should consult the references. It may be possible to place some of this data on tape should there be sufficient interest.

## References

- Cass, G.R. (1978), "Methods for Sulfate Air Quality Management with Applications to Los Angeles," Ph.D. thesis, Environmental Quality Laboratory, California Institute of Technology, Pasadena, 801 pp.
- Cass, G.R. (1979), "Sulfur Oxides Emissions in the Early 1980s under Conditions of Low Natural Gas Supply," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena.
- Hahn, R.W. (1981a), "An Assessment of the Viability of Marketable Permits," Ph.D. thesis, Environmental Quality Laboratory, California Institute of Technology, Pasadena.
- Hahn, R.W. (1981b), "Data Base and Programming Methodology for Marketable Permits Study," Open File Report No. 80-8, Environmental Quality Laboratory, California Institute of Technology, Pasadena.

Table 1

## Activities for Low Natural Gas Supply

## Number/Abbreviation/Description

1	EUR1	UTILITIES SWITCH FROM .025 TO .1 PCT S FUEL
2	EUR2	UTILITIES SWITCH FROM .1 TO .25 PCT S FUEL
3	EUR3	UTILITIES SWITCH FROM .25 TO .5 PCT S FUEL
4	EUR4	UTILITIES SWITCH FROM .5 TO 1 PCT S FUEL
5	EUR5	UTILITIES SWITCH FROM 1 TO 2.5 PCT S FUEL
6	EUR6	UTILITIES SWITCH FROM 2.5 TO 4 PCT S FUEL
7	EUD	UTILITIES DISTILLATE FUEL--UNCONTROLLED
8	RF1	REFINERY SWITCH FROM .025 TO .1 PCT S FUEL
9	RF2	REFINERY SWITCH FROM .1 TO .25 PCT S FUEL
10	RF3	REFINERY SWITCH FROM .25 TO .5 PCT S FUEL
11	RF4	REFINERY SWITCH FROM .5 TO 1 PCT S FUEL
12	RF5	REFINERY SWITCH FROM 1 TO 2.5 PCT S FUEL
13	RF6	REFINERY SWITCH FROM 2.5 TO 4 PCT S FUEL
14	NGL1	LOW PRIORITY NATURAL GAS CUSTOMERS--80 PCT SOX REMOVAL
15	NGL2	LOW PRIORITY NATURAL GAS CUSTOMERS--16 PCT SOX REMOVAL
16	NGH	HIGH PRIORITY NATURAL GAS CUSTOMERS--UNCONTROLLED
17	SRP	SULFUR RECOVERY PLANTS--UNCONTROLLED
18	SAP	SULFURIC ACID PLANTS--UNCONTROLLED
19	OC	OTHER CHEMICALS--UNCONTROLLED
20	FCC1	FLUID CATALYTIC CRACKERS--90 PCT SOX REMOVAL
21	FCC2	FLUID CATALYTIC CRACKERS--80 PCT SOX REMOVAL
22	SWS	SOUR WATER STRIPPERS--UNCONTROLLED
23	MRP	MISCELLANEOUS REFINERY PROCESS--UNCONTROLLED
24	OFP	OIL FIELD PRODUCTION
25	CCG1	GREAT LAKES CARBON--80 PCT SOX REMOVAL
26	CCG2	GREAT LAKES CARBON--70 PCT SOX REMOVAL
27	CCM	MARTIN MARIETTA CARBON--80 PCT SOX REMOVAL
28	GL1	GLASS PLANTS--.GT.95 PCT REMOVAL
29	GL2	GLASS PLANTS--ABOUT 85 PCT REMOVAL
30	GL3	GLASS PLANTS--ABOUT 15 PCT REMOVAL
31	NFM	NONFERROUS METALS--UNCONTROLLED
32	STL	FERROUS METALS--KAISER STEEL--REMOVE 80 PCT SOX AT \$400/T
33	MP	MINERAL PRODUCTS--UNCONTROLLED
34	STD	SEWAGE TREATMENT DIGESTERS--UNCONTROLLED
35	OIP	OTHER INDUSTRIAL PROCESSES--UNCONTROLLED
36	PI	PERMITTED INCINERATORS--UNCONTROLLED
37	CTS	CATALYST EQUIPPED LT. DUTY VEHICLES--SURFACE
38	CTF	CATALYST EQUIPPED LT. DUTY VEHICLES--FREEWAY
39	NCL	NONCATALYST LT. DUTY VEHICLES
40	HYD1	HEAVY HIGHWAY DIESEL VEHICLES--80 PCT SOX REMOVAL
41	HYD2	HEAVY HIGHWAY DIESEL VEHICLES--16 PCT SOX REMOVAL
42	AIR	AIRPORT OPERATIONS--UNCONTROLLED
43	SEA	SHIPPING OPERATIONS--UNCONTROLLED
44	RR1	RAILROAD OPERATIONS--80 PCT SOX REMOVAL
45	RR2	RAILROAD OPERATIONS--16 PCT SOX REMOVAL

Table 2

## Cost Data and References for Low Natural Gas Case

	<u>COLUMN 1</u>		<u>COLUMN 2</u>		<u>COLUMN 3</u>	
EUR1	4590.	D+0	60.28	D+0	20.09	D+0
EUR2	2720.	D+0	120.57	D+0	0.	D+0
EUR3	940.	D+0	200.95	D+0	0.	D+0
EUR4	470.	D+0	401.9	D+0	0.	D+0
EUR5	420.	D+0	1205.69	D+0	0.	D+0
EUR6	210.	D+0	1205.69	D+0	0.	D+0

Data on Electric Utilities Residual fuel burning are taken from Cass (1979)--Tables E1.5, E1.6 and E1.7. These are used in SOXDEM.2 to generate this data. See also:

Rogerson, W.P. (1980) "Electric Utilities" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena.

EUD	-1.	D+0	0.	D+0	2.12	D+0
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Electric Utilities Distillate fuel burning--uncontrolled  
Utility turbine fuel is already very high quality.

RF1	4590.	D+0	4.83	D+0	4.47	D+0
RF2	2720.	D+0	9.66	D+0	0.	D+0
RF3	940.	D+0	16.1	D+0	0.	D+0
RF4	470.	D+0	32.21	D+0	0.	D+0
RF5	420.	D+0	96.62	D+0	0.	D+0
RF6	210.	D+0	96.62	D+0	0.	D+0

## Refinery Fuel Burning

Uncontrolled  $2.86 + 1.61 = 4.47$

The 2.86 tons/day are the emissions from refinery gas (Table E1.14)

The 1.61 tons/day result from the fact that Rogerson assumes the cleanest fuel oil is .025 percent.

Refinery fuel burning--7365237. Bbl/Yr (Table E1.4--Cass)

Adjust Electric Utility demand curve to this quantity of oil.

This calculation is done automatically in SOXDEM.1.

NGL1	2000.	D+0	30.58	D+0	9.55	D+0
NGL2	1000.	D+0	7.64	D+0	0.	D+0

## Low Priority Natural Gas Customers

These numbers assume 80 percent of the sulfur can be removed.  
 The first 20 percent of the sulfur removed costs \$1000 per ton.  
 The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
 Environmental Quality Laboratory, California Institute  
 of Technology, Pasadena, March 12, 11 pp.

NGH    -1.                    D+0 0.            D+0 .27    D+0

High Priority Natural Gas Customers--uncontrolled

SRP    -1.                    D+0 0.            D+0 3.51   D+0

Sulfur Recovery Plants--uncontrolled

SAP    -1.                    D+0 0.            D+0 3.08   D+0

Sulfuric Acid Plants--uncontrolled

OC     -1.                    D+0 0.            D+0 .04    D+0

Other Chemicals--uncontrolled

FCC1   18700.            D+0 4.5            D+0 4.5    D+0

FCC2   810.                D+0 35.96          D+0 0.      D+0

Fluid Catalytic Crackers (80 and 90 percent control)  
 South Coast Air Quality Management District (1978) "Sulfur  
 Dioxide/Sulfate Control Study--Executive Summary,"  
 El Monte, California, p. 25.

SWS    -1.                    D+0 0.            D+0 1.03    D+0

Sour Water Strippers--uncontrolled

MRP    -1.                    D+0 0.            D+0 .76    D+0

Miscellaneous Refinery Processes--uncontrolled

OFF    200.                D+0 3.87            D+0 .43    D+0

Oil Field Production

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

CCG1	920.	D+0	1.52	D+0	3.05	D+0
CCG2	650.	D+0	10.67	D+0	0.	D+0
CCM	1320.	D+0	3.56	D+0	1.52	D+0

#### Petroleum Coke Calciners

Hahn, R.W. (1980) "Petroleum Coke Calciners" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, (revised using MM and GLC data).

GL1	46323.	D+0	.1	D+0	0.	D+0
GL2	19168.	D+0	.13	D+0	0.	D+0
GL3	2199.	D+0	2.	D+0	0.	D+0

#### Glass Plants

Figures have been scaled to reflect on and off-grid emissions.  
2.23 Tons SOx/day = total; 2 Tons SOx/day = on-grid.

Paranjape, A. (1980) "Glass Manufacturing" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, p. 30, Table 7.

NFM	-1.	D+0	0.	D+0	.98	D+0
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#### Nonferrous Metals--uncontrolled

STL	400.	D+0	9.5	D+0	5.05	D+0
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Fox, G. (1981), "Sulfur Abatement at Kaiser Steel," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, (received February 20).

MP	-1.	D+0	0.	D+0	1.9	D+0
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#### Mineral Products--uncontrolled

STD	-1.	D+0	0.	D+0	.64	D+0
-----	-----	-----	----	-----	-----	-----

#### Sewage Treatment Digesters--uncontrolled

OIP    -1.                    D+0  0.            D+0 .02        D+0

Other Industrial Processes--uncontrolled

PI      -1.                    D+0  0.            D+0 .07        D+0

Permitted Incinerators--uncontrolled

CTS     3600.                  D+0  1.93        D+0 5.77        D+0

Catalyst Equipped Light Duty Vehicles--surface

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

CTF     3600.                  D+0  1.34        D+0 4.02        D+0

Catalyst Equipped Light Duty Vehicles--freeway

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

NCL     3600.                  D+0  3.97        D+0 11.89        D+0

Noncatalyst Light Duty Vehicles

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

HYD1    2000.                  D+0  11.96        D+0 3.74        D+0

HYD2    1000.                  D+0  2.99        D+0 0.            D+0

Heavy Highway Diesel Vehicles

These numbers assume 80 percent of the sulfur can be removed.  
The first 20 percent of the sulfur removed costs \$1000 per ton.  
The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

AIR	-1.	D+0	0.	D+0	1.02	D+0
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Airport Operations--uncontrolled

SEA	-1.	D+0	0.	D+0	13.21	D+0
-----	-----	-----	----	-----	-------	-----

Shipping Operations--uncontrolled

RR1	2000.	D+0	2.77	D+0	.87	D+0
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RR2	1000.	D+0	.69	D+0	0.	D+0
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#### Railroad Operations

These numbers assume 80 percent of the sulfur can be removed.  
 The first 20 percent of the sulfur removed costs \$1000 per ton.  
 The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
 Environmental Quality Laboratory, California Institute  
 of Technology, Pasadena, March 12, 11 pp.

Table 3

## Activities for High Natural Gas Supply

## Number/Abbreviation/Description

1	EUR1	UTILITIES SWITCH FROM .025 TO .1 PCT S FUEL
2	EUR2	UTILITIES SWITCH FROM .1 TO .25 PCT S FUEL
3	EUR3	UTILITIES SWITCH FROM .25 TO .5 PCT S FUEL
4	EUR4	UTILITIES SWITCH FROM .5 TO 1 PCT S FUEL
5	EUR5	UTILITIES SWITCH FROM 1 TO 2.5 PCT S FUEL
6	EUR6	UTILITIES SWITCH FROM 2.5 TO 4 PCT S FUEL
7	EUD	UTILITIES DISTILLATE FUEL--UNCONTROLLED
8	RF	REFINERY GAS--UNCONTROLLED
9	NGL	LOW PRIORITY NATURAL GAS CUSTOMERS
10	NGH	HIGH PRIORITY NATURAL GAS CUSTOMERS--UNCONTROLLED
11	SRP	SULFUR RECOVERY PLANTS--UNCONTROLLED
12	SAP	SULFURIC ACID PLANTS--UNCONTROLLED
13	OC	OTHER CHEMICALS--UNCONTROLLED
14	FCC1	FLUID CATALYTIC CRACKERS--90 PCT SOX REMOVAL
15	FCC2	FLUID CATALYTIC CRACKERS--80 PCT SOX REMOVAL
16	SWS	SOUR WATER STRIPPERS--UNCONTROLLED
17	MRP	MISCELLANEOUS REFINERY PROCESS--UNCONTROLLED
18	OFP	OIL FIELD PRODUCTION
19	CCG1	GREAT LAKES CARBON--80 PCT SOX REMOVAL
20	CCG2	GREAT LAKES CARBON--70 PCT SOX REMOVAL
21	CCM	MARTIN MARIETTA CARBON--80 PCT SOX REMOVAL
22	GL1	GLASS PLANTS--GT.95 PCT REMOVAL
23	GL2	GLASS PLANTS--ABOUT 85 PCT REMOVAL
24	GL3	GLASS PLANTS--ABOUT 15 PCT REMOVAL
25	NFM	NONFERROUS METALS--UNCONTROLLED
26	STL	FERROUS METALS--KAISER STEEL--REMOVE 80 PCT SOX AT \$400/T
27	MP	MINERAL PRODUCTS--UNCONTROLLED
28	STD	SEWAGE TREATMENT DIGESTERS--UNCONTROLLED
29	OIP	OTHER INDUSTRIAL PROCESSES--UNCONTROLLED
30	PI	PERMITTED INCINERATORS--UNCONTROLLED
31	CTS	CATALYST EQUIPPED LT. DUTY VEHICLES--SURFACE
32	CTF	CATALYST EQUIPPED LT. DUTY VEHICLES--FREEWAY
33	NCL	NONCATALYST LT. DUTY VEHICLES
34	HYD1	HEAVY HIGHWAY DIESEL VEHICLES--80 PCT SOX REMOVAL
35	HYD2	HEAVY HIGHWAY DIESEL VEHICLES--16 PCT SOX REMOVAL
36	AIR	AIRPORT OPERATIONS--UNCONTROLLED
37	SEA	SHIPPING OPERATIONS--UNCONTROLLED
38	RR1	RAILROAD OPERATIONS--80 PCT SOX REMOVAL
39	RR2	RAILROAD OPERATIONS--16 PCT SOX REMOVAL

Table 4

## Cost Data and References for High Natural Gas Case

	<u>COLUMN 1</u>		<u>COLUMN 2</u>		<u>COLUMN 3</u>	
EUR1	4590.	D+0	13.87	D+0	4.62	D+0
EUR2	2720.	D+0	27.73	D+0	0.	D+0
EUR3	940.	D+0	46.22	D+0	0.	D+0
EUR4	470.	D+0	92.44	D+0	0.	D+0
EUR5	420.	D+0	277.31	D+0	0.	D+0
EUR6	210.	D+0	277.31	D+0	0.	D+0

Data on Electric Utilities Residual fuel burning are taken from Cass (1979)--Tables E1.5, E1.6 and E1.7. These are used in SOXDEM.3 to generate this data. See also:

Rogerson, W.P. (1980) "Electric Utilities" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena.

Cass, G.R. (1975) "Dimensions of the Los Angeles SO<sub>2</sub>/Sulfate Problem," EQL Memorandum No. 15, Environmental Quality Laboratory, California Institute of Technology, Pasadena, Appendix AI.

For the years 1970 and 1971, 77 percent of the fuel burned was natural gas. This figure is used to generate the utility demand.

EUD	-1.	D+0	0.	D+0	.49	D+0
-----	-----	-----	----	-----	-----	-----

Electric Utilities Distillate fuel burning--uncontrolled Utility turbine fuel is already very high quality.  $(1-.77)*(2.12)=.49$  The figure used for the low natural gas scenario was 2.12.

RF	-1.	D+0	0.	D+0	2.86	D+0
----	-----	-----	----	-----	------	-----

Refinery Fuel Burning  
Uncontrolled 2.86 Tons SO<sub>x</sub>/day  
The 2.86 tons/day are the emissions from refinery gas (Table E1.14)  
All other fuel used in refinery operations is presumed to be natural gas.

NGL	-1.	D+0	0.	D+0	0.	D+0
-----	-----	-----	----	-----	----	-----

## Low Priority Natural Gas Customers

This number is based on the assumption that these users burn only natural gas.

NGH    -1.                    D+0 0.                    D+0 .27                    D+0

High Priority Natural Gas Customers--uncontrolled

SRP    -1.                    D+0 0.                    D+0 3.51                    D+0

Sulfur Recovery Plants--uncontrolled

SAP    -1.                    D+0 0.                    D+0 3.08                    D+0

Sulfuric Acid Plants--uncontrolled

OC     -1.                    D+0 0.                    D+0 .04                    D+0

Other Chemicals--uncontrolled

FCC1   18700.                D+0 4.5                    D+0 4.5                    D+0  
FCC2   810.                    D+0 35.96                    D+0 0.                    D+0

Fluid Catalytic Crackers (80 and 90 percent control)  
South Coast Air Quality Management District (1978) "Sulfur  
Dioxide/Sulfate Control Study--Executive Summary,"  
El Monte, California, p. 25.

SWS    -1.                    D+0 0.                    D+0 1.03                    D+0

Sour Water Strippers--uncontrolled

MRP    -1.                    D+0 0.                    D+0 .76                    D+0

Miscellaneous Refinery Processes--uncontrolled

OFF    200.                    D+0 3.87                    D+0 .43                    D+0

Oil Field Production

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

CCG1	920.	D+0	1.52	D+0	3.05	D+0
CCG2	650.	D+0	10.67	D+0	0.	D+0
CCM	1320.	D+0	3.56	D+0	1.52	D+0

#### Petroleum Coke Calciners

Hahn, R.W. (1980) "Petroleum Coke Calciners" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, (revised using MM and GLC data).

GL1	46323.	D+0	.1	D+0	0.	D+0
GL2	19168.	D+0	.13	D+0	0.	D+0
GL3	2199.	D+0	2.	D+0	0.	D+0

#### Glass Plants

Figures have been scaled to reflect on and off-grid emissions.  
2.23 Tons SOx/day = total; 2 Tons SOx/day = on-grid.

Paranjape, A. (1980) "Glass Manufacturing" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, p. 30, Table 7.

NFM	-1.	D+0	0.	D+0	.98	D+0
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#### Nonferrous Metals—uncontrolled

STL	400.	D+0	9.5	D+0	5.05	D+0
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Fox, G. (1981), "Sulfur Abatement at Kaiser Steel," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, (received February 20).

MP	-1.	D+0	0.	D+0	1.9	D+0
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#### Mineral Products—uncontrolled

STD	-1.	D+0	0.	D+0	.64	D+0
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#### Sewage Treatment Digesters—uncontrolled

OIP	-1.	D+0	0.	D+0	.02	D+0
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## Other Industrial Processes--uncontrolled

PI	-1.	D+0	0.	D+0	.07	D+0
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## Permitted Incinerators--uncontrolled

CTS	3600.	D+0	1.93	D+0	5.77	D+0
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## Catalyst Equipped Light Duty Vehicles--surface

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

CTF	3600.	D+0	1.34	D+0	4.02	D+0
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## Catalyst Equipped Light Duty Vehicles--freeway

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

NCL	3600.	D+0	3.97	D+0	11.89	D+0
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## Noncatalyst Light Duty Vehicles

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

HYD1	2000.	D+0	11.96	D+0	3.74	D+0
HYD2	1000.	D+0	2.99	D+0	0.	D+0

## Heavy Highway Diesel Vehicles

These numbers assume 80 percent of the sulfur can be removed. The first 20 percent of the sulfur removed costs \$1000 per ton. The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

AIR	-1.	D+0	0.	D+0	1.02	D+0
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Airport Operations—uncontrolled

SEA	-1.	D+0	0.	D+0	13.21	D+0
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Shipping Operations—uncontrolled

RR1	2000.	D+0	2.77	D+0	.87	D+0
RR2	1000.	D+0	.69	D+0	0.	D+0

Railroad Operations

These numbers assume 80 percent of the sulfur can be removed.  
 The first 20 percent of the sulfur removed costs \$1000 per ton.  
 The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
 Environmental Quality Laboratory, California Institute  
 of Technology, Pasadena, March 12, 11 pp.

Table 5

## Activities for Historical Natural Gas Supply

## Number/Abbreviation/Description

1	EUR1	UTILITIES SWITCH FROM .025 TO .1 PCT S FUEL
2	EUR2	UTILITIES SWITCH FROM .1 TO .25 PCT S FUEL
3	EUR3	UTILITIES SWITCH FROM .25 TO .5 PCT S FUEL
4	EUR4	UTILITIES SWITCH FROM .5 TO 1 PCT S FUEL
5	EUR5	UTILITIES SWITCH FROM 1 TO 2.5 PCT S FUEL
6	EUR6	UTILITIES SWITCH FROM 2.5 TO 4 PCT S FUEL
7	RF1	REFINERY SWITCH FROM .025 TO .1 PCT S FUEL
8	RF2	REFINERY SWITCH FROM .1 TO .25 PCT S FUEL
9	RF3	REFINERY SWITCH FROM .25 TO .5 PCT S FUEL
10	RF4	REFINERY SWITCH FROM .5 TO 1 PCT S FUEL
11	RF5	REFINERY SWITCH FROM 1 TO 2.5 PCT S FUEL
12	RF6	REFINERY SWITCH FROM 2.5 TO 4 PCT S FUEL
13	NGL1	LOW PRIORITY N.G. SWITCH FROM .025 TO .1 PCT S FUEL
14	NGL2	LOW PRIORITY N.G. SWITCH FROM .1 TO .25 PCT S FUEL
15	NGL3	LOW PRIORITY N.G. SWITCH FROM .25 TO .5 PCT S FUEL
16	NGL4	LOW PRIORITY N.G. SWITCH FROM .5 TO 1. PCT S FUEL
17	NGL5	LOW PRIORITY N.G. SWITCH FROM 1. TO 2.5 PCT S FUEL
18	NGL6	LOW PRIORITY N.G. SWITCH FROM 2.5 TO 4. PCT S FUEL
19	NGH	HIGH PRIORITY NATURAL GAS CUSTOMERS--UNCONTROLLED
20	SRP	SULFUR RECOVERY PLANTS--UNCONTROLLED
21	SAP	SULFURIC ACID PLANTS--UNCONTROLLED
22	OC	OTHER CHEMICALS--UNCONTROLLED
23	FCC1	FLUID CATALYTIC CRACKERS--90 PCT SOX REMOVAL
24	FCC2	FLUID CATALYTIC CRACKERS--80 PCT SOX REMOVAL
25	SWS	SOUR WATER STRIPPERS--UNCONTROLLED
26	MRP	MISCELLANEOUS REFINERY PROCESS--UNCONTROLLED
27	OFFP	OIL FIELD PRODUCTION
28	CCG1	GREAT LAKES CARBON--80 PCT SOX REMOVAL
29	CCG2	GREAT LAKES CARBON--70 PCT SOX REMOVAL
30	CCM	MARTIN MARIETTA CARBON--80 PCT SOX REMOVAL
31	GL1	GLASS PLANTS REMOVE ALL BUT .1 TONS/DAY SOX--.GT.95 PCT REMOVAL
32	GL2	GLASS PLANTS REMOVE ALL BUT .31 TONS/DAY SOX--ABOUT 85 PCT REMOVAL
33	GL3	GLASS PLANTS REMOVE ABOUT .31 TONS/DAY SOX--ABOUT 15 PCT REMOVAL
34	NFM	NONFERROUS METALS--UNCONTROLLED
35	STL	FERROUS METALS--KAISER STEEL--OPTION TO REMOVE 80 PCT SOX AT \$400/T
36	MP	MINERAL PRODUCTS--UNCONTROLLED
37	STD	SEWAGE TREATMENT DIGESTERS--UNCONTROLLED
38	OIP	OTHER INDUSTRIAL PROCESSES--UNCONTROLLED
39	PI	PERMITTED INCINERATORS--UNCONTROLLED
40	CTS	CATALYST EQUIPPED LT. DUTY VEHICLES--SURFACE
41	CTF	CATALYST EQUIPPED LT. DUTY VEHICLES--FREEWAY
42	NCL	NONCATALYST LT. DUTY VEHICLES
43	HYD1	HEAVY HIGHWAY DIESEL VEHICLES--80 PCT SOX REMOVAL
44	HYD2	HEAVY HIGHWAY DIESEL VEHICLES--16 PCT SOX REMOVAL
45	AIR	AIRPORT OPERATIONS--UNCONTROLLED

46 SEA SHIPPING OPERATIONS--UNCONTROLLED  
47 RR1 RAILROAD OPERATIONS--80 PCT SOX REMOVAL  
48 RR2 RAILROAD OPERATIONS--16 PCT SOX REMOVAL

Table 6

## Cost Data and References for Historical Natural Gas Case

	<u>COLUMN 1</u>		<u>COLUMN 2</u>		<u>COLUMN 3</u>	
EUR1	4590.	D+0	41.02	D+0	13.67	D+0
EUR2	2720.	D+0	82.04	D+0	0.	D+0
EUR3	940.	D+0	136.74	D+0	0.	D+0
EUR4	470.	D+0	273.48	D+0	0.	D+0
EUR5	420.	D+0	820.43	D+0	0.	D+0
EUR6	210.	D+0	820.43	D+0	0.	D+0

Data on Electric Utilities Residual fuel burning are taken from Cass (1978)--PP. 493, 598. These are used in SOXDEM.6 to generate this data. See also:

Rogerson, W.P. (1980) "Electric Utilities" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena.

RF1	4590.	D+0	1.23	D+0	2.86	D+0
RF2	2720.	D+0	2.47	D+0	0.	D+0
RF3	940.	D+0	4.11	D+0	0.	D+0
RF4	470.	D+0	8.22	D+0	0.	D+0
RF5	420.	D+0	24.66	D+0	0.	D+0
RF6	210.	D+0	24.66	D+0	0.	D+0

## Refinery Fuel Burning

Uncontrolled  $2.45 + .41 = 2.86$

The 2.45 tons/day are the emissions from refinery gas.(Cass(1978),p.677)

The .41 tons/day result from the fact that Rogerson assumes the cleanest fuel oil is .025 percent.

Refinery fuel burning--1880241. Bbl/Yr (Cass(1978), pp. 500, 598)

Adjust Electric Utility demand curve to this quantity of oil.

This calculation is done automatically in SOXDEM.6.

NGL1	4590.	D+0	.48	D+0	.16	D+0
NGL2	2720.	D+0	.96	D+0	0.	D+0
NGL3	940.	D+0	1.6	D+0	0.	D+0
NGL4	470.	D+0	3.2	D+0	0.	D+0
NGL5	420.	D+0	9.59	D+0	0.	D+0
NGL6	210.	D+0	9.59	D+0	0.	D+0

Data on Low Priority Natural Gas Customers are taken from Cass (1978)--pp. 508, 598. The amount of oil burned by this class of sources is 731,141. The demand curve is

is generated in SOXDEM.6. This class is really Other Interruptible Gas Customers for this run. The two are very closely related.

NGH    -1.                    D+0  0.            D+0 .27    D+0

High Priority Natural Gas Customers—uncontrolled

SRP    -1.                    D+0  0.            D+0 3.51   D+0

Sulfur Recovery Plants—uncontrolled

SAP    -1.                    D+0  0.            D+0 3.08   D+0

Sulfuric Acid Plants—uncontrolled

OC     -1.                    D+0  0.            D+0 .04     D+0

Other Chemicals—uncontrolled

FCC1   18700.            D+0  4.5            D+0 4.5     D+0  
FCC2   810.                D+0 35.96           D+0 0.       D+0

Fluid Catalytic Crackers (80 and 90 percent control)  
South Coast Air Quality Management District (1978) "Sulfur  
Dioxide/Sulfate Control Study—Executive Summary,"  
El Monte, California, p. 25.

SWS    -1.                    D+0  0.            D+0 1.03    D+0

Sour Water Strippers—uncontrolled

MRP    -1.                    D+0  0.            D+0 .76     D+0

Miscellaneous Refinery Processes—uncontrolled

OFF    200.                    D+0  3.87            D+0 .43     D+0

Oil Field Production

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
Environmental Quality Laboratory, California Institute  
of Technology, Pasadena, March 12, 11 pp.

CCG1	920.	D+0	1.52	D+0	3.05	D+0
CCG2	650.	D+0	10.67	D+0	0.	D+0
CCM	1320.	D+0	3.56	D+0	1.52	D+0

#### Petroleum Coke Calciners

Hahn, R.W. (1980) "Petroleum Coke Calciners" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, (revised using MM and GLC data).

GL1	46323.	D+0	.1	D+0	0.	D+0
GL2	19168.	D+0	.13	D+0	0.	D+0
GL3	2199.	D+0	2.	D+0	0.	D+0

#### Glass Plants

Figures have been scaled to reflect on and off-grid emissions.  
2.23 Tons SOx/day = total; 2 Tons SOx/day = on-grid.

Paranjape, A. (1980) "Glass Manufacturing" in "Implementing Tradable Emissions Licenses: Sulfur Oxides in the Los Angeles Air Shed", Environmental Quality Laboratory, California Institute of Technology, Pasadena, p. 30, Table 7.

NFM	-1.	D+0	0.	D+0	.98	D+0
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#### Nonferrous Metals--uncontrolled

STL	400.	D+0	9.5	D+0	5.05	D+0
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Fox, G. (1981), "Sulfur Abatement at Kaiser Steel," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, (received February 20).

MP	-1.	D+0	0.	D+0	1.9	D+0
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#### Mineral Products--uncontrolled

STD	-1.	D+0	0.	D+0	.64	D+0
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#### Sewage Treatment Digesters--uncontrolled

OIP	-1.	D+0	0.	D+0	.02	D+0
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## Other Industrial Processes--uncontrolled

PI	-1.	D+0	0.	D+0	.07	D+0
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## Permitted Incinerators--uncontrolled

CTS	3600.	D+0	1.93	D+0	5.77	D+0
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## Catalyst Equipped Light Duty Vehicles--surface

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

CTF	3600.	D+0	1.34	D+0	4.02	D+0
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## Catalyst Equipped Light Duty Vehicles--freeway

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

NCL	3600.	D+0	3.97	D+0	11.89	D+0
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## Noncatalyst Light Duty Vehicles

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

HYD1	2000.	D+0	11.96	D+0	3.74	D+0
HYD2	1000.	D+0	2.99	D+0	0.	D+0

## Heavy Highway Diesel Vehicles

These numbers assume 80 percent of the sulfur can be removed. The first 20 percent of the sulfur removed costs \$1000 per ton. The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper, Environmental Quality Laboratory, California Institute of Technology, Pasadena, March 12, 11 pp.

AIR	-1.	D+0	0.	D+0	1.02	D+0
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## Airport Operations--uncontrolled

SEA	-1.	D+0	0.	D+0	13.21	D+0
-----	-----	-----	----	-----	-------	-----

Shipping Operations—uncontrolled

RR1	2000.	D+0	2.77	D+0	.87	D+0
RR2	1000.	D+0	.69	D+0	0.	D+0

Railroad Operations

These numbers assume 80 percent of the sulfur can be removed.  
 The first 20 percent of the sulfur removed costs \$1000 per ton.  
 The latter 80 percent of the sulfur removed costs \$2000 per ton.

Hahn, R.W. (1981), "Petroleum Refiners," working paper,  
 Environmental Quality Laboratory, California Institute  
 of Technology, Pasadena, March 12, 11 pp.

Table 7  
Location of Air Quality Monitoring Sites

<u>Number</u>	<u>Location</u>
1	DOWNTOWN LOS ANGELES
2	AZUSA
3	WEST LOS ANGELES
4	LENNOX
5	PASADENA
6	LYNWOOD
7	SANTA MONICA
8	ANAHEIM
9	GARDEN GROVE
10	GLENDORA
11	WEST COVINA
12	TORRANCE
13	LONG BEACH
14	GLENDALE
15	SANTA ANA
16	SANTA FE SPRINGS
17	EAST LA (PEAK)

Table 8

## Source-Receptor Coefficients for Generic Activity Classes

## 1 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - DOWNTOWN LA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01606	0.02025	0.03163	0.03076	0.03479
2	0.01510	0.01379	0.03272	0.02392	0.02457
3	0.01757	0.01439	0.03687	0.03139	0.03564
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02740	0.02513	0.02255	0.01060	0.01758
2	0.02648	0.02635	0.01855	0.00520	0.01613
3	0.02916	0.02845	0.02449	0.00539	0.01463
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.06914	0.00238	0.01552	0.06616	0.30750
2	0.05566	0.00230	0.01303	0.05415	0.26151
3	0.07123	0.00190	0.01505	0.05938	0.28582
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02646	0.05296	0.04620	0.02626	0.12346
2	0.01790	0.04242	0.03132	0.02228	0.10460
3	0.02077	0.04691	0.03588	0.02521	0.11739

## 2 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - AZUSA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01734	0.02070	0.02984	0.02765	0.03112
2	0.01203	0.02995	0.03854	0.02459	0.04024
3	0.01437	0.02540	0.04102	0.02822	0.04679
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02828	0.02751	0.02433	0.01445	0.02297
2	0.04291	0.03830	0.03111	0.00924	0.03497
3	0.04406	0.03737	0.03564	0.01218	0.03660
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.05086	0.01114	0.01804	0.03495	0.12151
2	0.04386	0.00441	0.01447	0.02567	0.11235
3	0.05008	0.00570	0.01594	0.02847	0.12108
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02399	0.02944	0.01873	0.02333	0.03624
2	0.01720	0.02229	0.00831	0.02836	0.02761
3	0.01929	0.02487	0.00681	0.03128	0.03177

## 3 SOURCE CLASS CONTRIBUTION PER T/DAY OF SOX - WEST LOS ANGELES

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01216	0.01248	0.02186	0.02060	0.01870
2	0.00850	0.00943	0.01896	0.01361	0.01596
3	0.01050	0.01383	0.01911	0.01733	0.01781
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.01877	0.01844	0.01485	0.00511	0.01425
2	0.02006	0.01676	0.01418	0.00311	0.00976
3	0.01992	0.01820	0.01478	0.00492	0.01053
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.02578	0.00202	0.00905	0.05792	0.17116
2	0.01724	0.00112	0.00592	0.04854	0.14599
3	0.02223	0.00054	0.00756	0.05355	0.16191
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02088	0.04227	0.07055	0.01836	0.02869
2	0.01394	0.03406	0.04491	0.01407	0.01902
3	0.01615	0.03756	0.03973	0.01739	0.02292

## 4 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - LENNOX

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01381	0.01409	0.03201	0.01982	0.02784
2	0.00980	0.01092	0.03059	0.01525	0.02379
3	0.01184	0.01463	0.03792	0.01908	0.02880
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.03029	0.02640	0.02183	0.00927	0.01639
2	0.02858	0.02293	0.02000	0.00501	0.01787
3	0.03739	0.02837	0.02350	0.00562	0.01382
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03205	0.00198	0.00958	0.04561	0.13196
2	0.02214	0.00170	0.00711	0.03935	0.12001
3	0.03122	0.00156	0.00792	0.04206	0.13513
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01843	0.03493	0.11001	0.02312	0.04274
2	0.01291	0.02950	0.07956	0.02357	0.04009
3	0.01362	0.03116	0.06350	0.02787	0.04091

## 5 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - PASADENA

	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01564	0.02345	0.02751	0.03244	0.02633
2	0.01915	0.01648	0.02733	0.02927	0.02458
3	0.01833	0.01597	0.02958	0.03306	0.03249
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02090	0.02501	0.02274	0.01028	0.01725
2	0.02296	0.02417	0.02093	0.00655	0.01544
3	0.02658	0.02932	0.02216	0.00688	0.01588
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.05357	0.00314	0.01514	0.04803	0.13577
2	0.04964	0.00288	0.01493	0.03906	0.12949
3	0.06041	0.00247	0.01630	0.04410	0.13992
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02576	0.03625	0.02926	0.02054	0.04686
2	0.01860	0.02926	0.02977	0.01999	0.04445
3	0.02212	0.03312	0.03742	0.02292	0.05061

## 6 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - LYNWOOD

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01585	0.02424	0.04161	0.02643	0.03613
2	0.01012	0.01663	0.03473	0.01997	0.02880
3	0.01399	0.01891	0.04018	0.02423	0.03393
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.03529	0.03256	0.02751	0.01566	0.03338
2	0.03892	0.03308	0.02240	0.01225	0.02387
3	0.04239	0.03349	0.02337	0.01209	0.02152
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.05382	0.00322	0.01332	0.04734	0.14010
2	0.03879	0.00299	0.00961	0.03817	0.13442
3	0.04982	0.00371	0.01033	0.04051	0.14275
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02098	0.03587	0.02096	0.03318	0.05898
2	0.01434	0.02876	0.00812	0.03056	0.04792
3	0.01548	0.03054	0.00752	0.03269	0.04971

## 7 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - SANTA MONICA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01012	0.00871	0.02087	0.01615	0.02109
2	0.00549	0.01067	0.01706	0.01095	0.01278
3	0.00833	0.01233	0.01976	0.01351	0.01522
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.01972	0.01687	0.01329	0.00476	0.01305
2	0.01790	0.01436	0.01037	0.00391	0.00921
3	0.01660	0.01749	0.01256	0.00384	0.01218
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.01826	0.00034	0.00632	0.04009	0.08721
2	0.01361	0.00117	0.00514	0.03405	0.08195
3	0.01579	0.00067	0.00538	0.03768	0.09141
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01656	0.02971	0.05589	0.01821	0.02180
2	0.01096	0.02460	0.07356	0.01361	0.01373
3	0.01251	0.02694	0.07017	0.01707	0.01604

## 8 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - ANAHEIM

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01496	0.02364	0.01989	0.01424	0.01969
2	0.00653	0.00718	0.00556	0.00700	0.00631
3	0.00675	0.00897	0.00436	0.00743	0.00555
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.01904	0.01813	0.01978	0.03283	0.02338
2	0.00590	0.00475	0.00701	0.03250	0.00667
3	0.00485	0.00435	0.00631	0.03357	0.00431
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.02446	0.00912	0.01531	0.03824	0.16586
2	0.02123	0.01074	0.01113	0.02924	0.15357
3	0.02163	0.00659	0.01218	0.03105	0.16451
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01580	0.03131	0.00762	0.02520	0.03090
2	0.00932	0.02407	0.00303	0.00927	0.02328
3	0.00997	0.02558	0.00387	0.01075	0.02346

## 9 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - GARDEN GROVE

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01376	0.01803	0.01596	0.01234	0.02022
2	0.00586	0.00394	0.00487	0.00617	0.00551
3	0.00579	0.00464	0.00370	0.00632	0.00503
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.01620	0.01624	0.01758	0.04105	0.02218
2	0.00419	0.00391	0.00463	0.02905	0.00555
3	0.00353	0.00346	0.00454	0.04698	0.00287
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.02903	0.00761	0.01457	0.03461	0.16013
2	0.02397	0.00760	0.01049	0.02664	0.13888
3	0.02781	0.00651	0.01324	0.02804	0.14403
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01438	0.02896	0.00927	0.02382	0.02666
2	0.00854	0.02185	0.00404	0.00866	0.01895
3	0.00901	0.02303	0.00370	0.00855	0.01850

## 10 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - GLENDORA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01719	0.02259	0.02714	0.02623	0.03305
2	0.01464	0.04183	0.04017	0.02057	0.05377
3	0.01515	0.04472	0.03950	0.02306	0.04701
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02800	0.02694	0.02499	0.01454	0.02424
2	0.04156	0.03563	0.04029	0.01387	0.04339
3	0.03554	0.03720	0.04063	0.01473	0.04387
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03852	0.00984	0.02048	0.03263	0.08394
2	0.02710	0.00900	0.01581	0.02450	0.06951
3	0.03086	0.01172	0.01756	0.02696	0.07499
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02288	0.02618	0.02214	0.02422	0.03326
2	0.01600	0.01935	0.00587	0.03273	0.02603
3	0.01770	0.02126	0.00777	0.03598	0.02965

## 11 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - WEST COVINA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01719	0.02359	0.03140	0.02866	0.03978
2	0.01401	0.04045	0.03958	0.02116	0.04926
3	0.01204	0.04200	0.04372	0.02378	0.06082
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02860	0.02621	0.02957	0.01823	0.02688
2	0.03743	0.03704	0.04142	0.01315	0.04134
3	0.04272	0.03955	0.03758	0.01845	0.04558
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.04997	0.00818	0.02154	0.03719	0.13533
2	0.02602	0.00445	0.01719	0.02745	0.10296
3	0.02966	0.00633	0.01901	0.03001	0.10919
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02364	0.03141	0.02665	0.02582	0.03846
2	0.01581	0.02258	0.00531	0.03804	0.02800
3	0.01744	0.02502	0.00539	0.03746	0.03202

## 12 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - TORRANCE

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01069	0.01229	0.03639	0.01867	0.03014
2	0.00821	0.01554	0.02932	0.01337	0.02774
3	0.00886	0.01777	0.03564	0.01742	0.03484
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.03619	0.02968	0.02355	0.01223	0.02241
2	0.02447	0.02170	0.02125	0.00603	0.02579
3	0.03695	0.02764	0.02469	0.01138	0.02749
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03080	0.00262	0.00991	0.03991	0.11392
2	0.02773	0.00245	0.00686	0.03287	0.10915
3	0.03164	0.00237	0.00706	0.03459	0.11814
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01642	0.03019	0.02301	0.03494	0.04134
2	0.01117	0.02449	0.01950	0.03058	0.03676
3	0.01119	0.02525	0.01098	0.03604	0.03650

## 13 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - LONG BEACH

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01342	0.03881	0.03568	0.01756	0.03472
2	0.00776	0.03693	0.02810	0.01154	0.02687
3	0.01054	0.04463	0.03393	0.01384	0.03160
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.03005	0.03225	0.02797	0.01583	0.03546
2	0.02407	0.02245	0.02717	0.01398	0.03592
3	0.02862	0.02600	0.03385	0.01634	0.05117
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.02080	0.00288	0.00958	0.03538	0.19350
2	0.01601	0.00388	0.00774	0.02875	0.16903
3	0.01595	0.00354	0.00848	0.02980	0.18393
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01682	0.03273	0.01975	0.05117	0.05315
2	0.01083	0.02597	0.01037	0.05319	0.04521
3	0.01100	0.02714	0.00772	0.06087	0.04673

## 14 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - GLENDALE

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01389	0.01481	0.02415	0.02682	0.02086
2	0.01072	0.01113	0.01962	0.02110	0.01727
3	0.01260	0.01718	0.02095	0.02504	0.02277
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02376	0.01937	0.01781	0.00553	0.01598
2	0.01826	0.01781	0.01271	0.00389	0.01047
3	0.01977	0.02065	0.01731	0.00451	0.01250
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03536	0.00326	0.01207	0.04762	0.16725
2	0.02948	0.00231	0.01032	0.04016	0.13579
3	0.03532	0.00099	0.01273	0.04539	0.14699
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02462	0.03635	0.04016	0.01964	0.03749
2	0.01761	0.02879	0.04136	0.01598	0.02636
3	0.02125	0.03318	0.04982	0.01824	0.03205

## 15 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - SANTA ANA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01716	0.01909	0.01228	0.00968	0.01024
2	0.00751	0.00296	0.00305	0.00458	0.00473
3	0.00711	0.00311	0.00243	0.00435	0.00363
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.00974	0.01153	0.01145	0.04767	0.01412
2	0.00204	0.00228	0.00396	0.06326	0.00257
3	0.00244	0.00217	0.00247	0.07245	0.00241
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03414	0.00807	0.01802	0.02943	0.17589
2	0.02161	0.00733	0.01717	0.02233	0.15864
3	0.03137	0.00828	0.01866	0.02333	0.16754
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.01233	0.02631	0.00919	0.02015	0.02140
2	0.00728	0.02009	0.00620	0.00542	0.01347
3	0.00740	0.02121	0.00577	0.00434	0.01370

## 16 SOURCE CLASS CONTRIBUTION PER T/DAY OF SOX - SANTA FE SPRINGS

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01814	0.03286	0.04221	0.02479	0.05463
2	0.01062	0.03333	0.05141	0.01841	0.05013
3	0.01423	0.03466	0.05585	0.02166	0.06526
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.04221	0.03612	0.03669	0.02054	0.04637
2	0.04625	0.04073	0.04343	0.01716	0.05274
3	0.04816	0.04128	0.03934	0.01317	0.06201
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.03629	0.00347	0.01582	0.04964	0.22360
2	0.02200	0.00457	0.00985	0.03933	0.20541
3	0.03072	0.00405	0.01328	0.04249	0.22323
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02220	0.04117	0.02347	0.03295	0.04668
2	0.01480	0.03324	0.00690	0.04545	0.03966
3	0.01627	0.03605	0.00786	0.04663	0.04081

## 17 SOURCE CLASS CONTRIBUTION PER TON/DAY OF SOX - EAST LA

YEAR	UTILITY RESID.	UTILITY DIST OIL	REFINERY FUEL	OTHER FUEL	SULFUR PLANTS
1	0.01820	0.01960	0.03005	0.03492	0.03135
2	0.01684	0.01397	0.02938	0.03024	0.03419
3	0.02047	0.01777	0.03446	0.03670	0.03390
	SULFURIC ACID	REFINERY FCC UNIT	OTHER REFINERY	OIL FIELDS	COKE KILNS
1	0.02441	0.02741	0.02424	0.01179	0.01843
2	0.02607	0.03191	0.02237	0.00824	0.01802
3	0.03095	0.02844	0.02612	0.00960	0.02160
	GLASS FURNACES	FERROUS METALS	MISC. UNITS	CAT AUTO STREET	CAT AUTO FREEWAY
1	0.08963	0.00440	0.01793	0.05405	0.28893
2	0.09189	0.00217	0.01349	0.04246	0.23985
3	0.11531	0.00176	0.01691	0.04672	0.25984
	NON-CAT VEHICLES	DIESEL VEHICLES	AIRPORT	SHIPPING	RAILROAD
1	0.02647	0.04694	0.03420	0.02384	0.09142
2	0.01770	0.03665	0.01078	0.02159	0.07850
3	0.02043	0.04019	0.01509	0.02630	0.08586

TABLE 10

Tabulation of Estimated Sulfate  
Background Concentrations  
for the South Coast Air Basin  
(in  $\mu\text{gm}/\text{m}^3$  as  $\text{SO}_4^{=}$ )

Month	1972		1973		1974	
	Vista	Background Estimate at 40% of Vista	Vista	Background Estimate at 40% of Vista	Vista	Background Estimate at 40% of Vista
January	6.03	2.41	5.87	2.35	6.78	2.71
February	11.07	4.43	4.98	1.99	6.50	2.60
March	14.12	5.65	3.28	1.31	7.21	2.88
April	8.03	3.21	6.54	2.62	6.43	2.57
May	9.78	3.91	10.32	4.13	9.84	3.94
June	16.12	6.45	11.39	4.56	8.55	3.42
July	8.14	3.26	19.25	7.70	7.76	3.10
August	11.73	4.69	17.71	7.08	12.35	4.94
September	9.16	3.66	14.02	5.61	13.98	5.59
October	7.91	3.16	11.03	4.41	12.17	4.87
November	4.90	1.96	6.66	2.66	7.40	2.96
December	5.75	2.30	7.93	3.17	4.87	1.95
Unweighted Mean		3.76		3.97		3.46

Note: Background sulfate concentrations are estimated from the seasonal trend in sulfates observed at Vista, scaled to the level of the average sulfate concentrations measured at San Nicolas Island. Sulfates at Vista during the months of July through October averaged  $12.15 \mu\text{gm}/\text{m}^3$  (3 year mean) versus an average of  $4.9 \mu\text{gm}/\text{m}^3$  at San Nicolas Island in that season of the year (see Table 2.1). Background sulfate concentrations at San Nicolas Island are approximately 40% of those at Vista, our most remote site with enough data to estimate seasonal trends in background concentrations.